UNIVERSITY OF
WATERLOO

School of Computer Science

CS 343
Concurrent and Parallel Programming

Course Notes[*] Fall 2025

https://www.student.cs.uwaterloo.ca/~cs343

μC++ download or Github (installation: `sudo sh u++-7.0.0.sh`)

September 4, 2025

Outline

An introduction to concurrent programming, with an emphasis on language constructs. Major topics include: exceptions, coroutines, atomic operations, critical sections, mutual exclusion, semaphores, high-level concurrency, deadlock, interprocess communication, process structuring on shared memory architectures. Students learn how to structure, implement and debug complex control-flow.

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Contents

1 Advanced Control Flow (Review)

- *Within* a routine, basic and advanced control structures allow virtually any control flow.
- For predicate only, **while** and **for** are interchangeable.

GOOD

```
while ( predicate ) {
     S1
}
```

GOOD

```
for ( ; predicate ; ) {
     S1
}
```

for allows adding/removing loop index for debugging.

- Do not use **while** to simulate **for**.

BAD

```
int i = 0;
while ( i < 10 ) {
     S1
     i += 1;
}
```

GOOD

```
for ( int i = 0; i < 10; i +=1 ) {
     S1

}
```

- **while**/**for** tests/exits loop at top; **do**–**while** tests/exits loop at botton.
- **Multi-exit loop** (or mid-test loop) exits at one or more locations **within** the loop body.

```
for ( ;; ) {                    // infinite loop, while ( true )
     . . .
  if ( . . . ) break;           // middle exit
     . . .
}
```

- Exit condition *reversed* from **while** and *outdented* (eye-candy) for readability
- Eliminates priming (duplicated) code necessary with **while**.

```
cin >> d; // priming
while ( ! cin.fail() ) {
     . . .
     cin >> d;
}
```

```
for ( ;; ) {
     cin >> d;
  if ( cin.fail() ) break;
     . . .
}
```

- Do not use multi-exit to simulate **while**/**for**, especially for loop index.

BAD

```
for ( int i = 0; ; i += 1 ) {
  if ( i == 10 ) break;
     S1
}
```

GOOD

```
for ( int i = 0; i < 10; i += 1 ) {

     S1
}
```

- A loop exit **NEVER** needs an **else** clause.

```
        BAD           |        GOOD            |        BAD           |        GOOD
for ( ;; ) {          | for ( ;; ) {           | for ( ;; ) {         | for ( ;; ) {
    S1                |     S1                 |     S1               |     S1
    if ( C1 ) {       |   if ( ! C1 ) break;   |     if ( C1 ) {      |   if ( C1 ) break;
        S2            |     S2                 |         break;       |
    } else {          |                        |     } else {         |
        break;        |                        |         S2           |     S2
    }                 |                        |     }                |
    S3                |     S3                 |     S3               |     S3
}                     | }                      | }                    | }
```

S2 is logically part of loop body ***not*** part of an **if**.

- Allow multiple exit conditions.

```
                                | bool flag1 = false, flag2 = false;
for ( ;; ) {                    | while ( ! flag1 && ! flag2 ) {
    S1                          |     S1
  if ( C1 ) { E1; break; }      |     if ( C1 ) flag1 = true;
                                |     } else {
    S2                          |         S2
  if ( C2 ) { E2; break; }      |         if ( C2 ) flag2 = true;
                                |         } else {
    S3                          |             S3
}                               |         }
                                |     }
                                | }
                                | if ( flag1 ) E1;
                                | else E2;
```

- Eliminate **flag variable**s used solely to affect control flow, i.e., variable does not contain data associated with computation.

- ***Flag variables are the variable equivalent to a goto*** because they can be set/reset/tested at arbitrary locations in a program.

1.1 Static multi-level exit

- **Static multi-level exit** exits multiple control structures where exit point is *known* at compile time.

- Labelled exit (**break/continue**) provides this capability.

μC++ / Java

```
BK: { // good eye-candy
     ... declarations ...
     SW: switch ( ... ) {
          FR: for ( ... ) {
               ... break BK; ... // exit block
               ... break SW; ... // exit switch
               ... break FR; ... // exit loop
          }
          ...
     }
     ...
}
```

C / C++

```
{
     ... declarations ...
     switch ( ... ) {
          for ( ... ) {
               ... goto BK; ...
               ... goto SW; ...
               ... goto FR; ... // or break
          } FR: ;
          ...
     } SW: ; // bad eye-candy
     ...
} BK: ;
```

- Why is it good practice to label all exits?
- Eliminate all flag variables with multi-level exit!

```
F1: for ( i = 0; i < 10; i += 1 ) {

     F2: for ( j = 0; j < 10; j += 1 ) {

               ...
       if ( ... ) break F2;   // outdent

               ...  // rest of loop
  if ( ... ) break F1;   // outdent

               ...  // rest of loop


     } // for

     ...  // rest of loop

} // for
```

```
bool flag1 = false;
for ( i = 0; i < 10 && ! flag1; i += 1 ) {
     bool flag2 = false;
     for ( j = 0; j < 10 &&
           ! flag1 && ! flag2; j += 1 ) {
          ...
          if ( ... ) flag2 = true;
          else {
               ...  // rest of loop
               if ( ... ) flag1 = true;
               else {
                    ...  // rest of loop
               } // if
          } // if
     } // for
     if ( ! flag1 ) {
          ...  // rest of loop
     } // if
} // for
```

- **Occasionally a flag variable is necessary!**

```
// Retain state from one inner lexical (static) scope to another.
int val;   bool valDefault = false;
switch ( argc ) {
  ...
  case 3:
     if ( strcmp( argv[4], "d" ) ) valDefault = true; // default ?
     else val = stoi( argv[4] ); // value
  ...
} // switch
```

```
for ( ;; ) {
    . . .
    if ( valDefault ) // do something
    else // do another
    . . .
} // for
```

- Other uses of multi-level exit to remove duplicate code.

duplication

```
if ( C1 ) {
    S1;
    if ( C2 ) {
        S2;
        if ( C3 ) {
            S3;
        } else
            S4;
    } else
        S4;
} else
    S4;
```

no duplication

```
C: {
    if ( C1 ) {
        S1;
        if ( C2 ) {
            S2;
            if ( C3 ) {
                S3;
  break C;
            }
        }
    }
    S4; // only once
}
```

```
{
  if ( C1 ) {
      S1;
      if ( C2 ) {
          S2;
          if ( C3 ) {
              S3;
              goto C;
          }
      }
  }
  S4; // only once
} C: ;
```

- Normal and labelled **break** are a **goto** with limitations.
  1. Cannot loop (only forward branch) ⇒ only loop constructs branch back.
  2. Cannot branch ***into*** a control structure.
- **Only use goto to perform static multi-level exit, e.g., simulate labelled break and continue.**

1.2 Dynamic Memory Allocation

- Stack allocation eliminates explicit storage-management and is more efficient than heap allocation — **“Use the STACK, Luke.”**

```
{ // GOOD, use stack
    cin >> size;
    int arr[size]; // VLA, g++
    . . . // use arr[i]

}
```

```
{ // BAD, unnecessary dynamic allocation
    cin >> size;
    int * arr = new int[size];
    . . . // use arr[i]
    delete [] arr; // why “[]”?
}
```

  - Increase stack size (kilobytes) from shell (bash):

```
$ ulimit -s        # current stack limit
16384
$ ulimit -s unlimited
$ ulimit -s        # new stack limit
unlimited
```

- These are the situations where dynamic (heap) allocation is necessary.
  1. When storage must outlive the block in which it is allocated (ownership change).

```
Type * rtn(...) {
    Type * tp = new Type;     // MUST USE HEAP
    ...                       // initialize/compute using tp
    return tp;                // storage outlives block
}                             // tp deleted later
```

Similar to necessary flag variable: to retain state from a lower level.

2. When the amount of data read is unknown.

```
vector<int> input;
int temp;
for ( ;; ) {
    cin >> temp;
  if ( cin.fail() ) break;
    input.push_back( temp ); // implicit dynamic allocation
}
```

Does switching to emplace_back help?

3. When the array elements must be initialized via the object's constructor to different values.

```
struct S {
    const int id; ... // possibly other fields
    S( int id ) : id{ id } { ... }
};

cin >> size;
S sa[size]; // no default constructor! declaration fails
for ( int id = 0; id < size; id += 1 )
    sa[id].id = id; // S::id is const! assignment fails
```

- Must use explicit pointers and dynamic allocation or unique_ptr (left/right same).

```
S * sa[size];
for ( int id = 0; id < size; id += 1 )
    sa[id] = new S{ id };
...
for ( int id = 0; id < size; id += 1 )
    delete sa[id];
```

```
{ // BAD, use heap
    unique_ptr<S> sa[size];
    for ( int id = 0; id < size; id += 1 )
        sa[id] = make_unique<S>( id );
    ...
} // implicit array deallocate
```

- μC++ provides macro uArray for declaring a single-dimension VLA array.

```
{ // GOOD, use stack
    uArray( S, sa, size ); // macro
    for ( int id = 0; id < size; id += 1 )
        sa[id]( id ); // constructor call
    ...
} // implicit array deallocate
```

- Like unique_ptr, uArray allocates sa without element constructor calls (placement **new** allocation) **and it proves subscript checking**.
- Calls to (...) or make_unique<T>(...) initialize array elements.
- Allocation for uArray is $O(1)$ in stack; unique_ptr is $O(N)$ in heap.
- As for unique_ptr, use * for object and -> for field access.

```
for ( int id = 0; id < size; id += 1 )
    cout << *sa[id] << ' ' << sa[id]->id << endl;
```

- When possible, use uArray instead of std::unique_ptr or std::vector as both use the heap.
- Use uArrayFill to initialize all elements to same value.

```
uArrayFill( S, sa, size, 42 ); // declare and initialize all elements to 42
```

- size member returns array size.

```
for ( int id = 0; id < sa.size(); id += 1 )
```

- uArray assignment allowed if the array elements are assignable.

```
uArray( S, sa2, sa.size() - 5 );
sa2 = sa; // copy minimum array-size elements
```

- Cannot pass uArray (or uArrayPtr) by value; pass by reference with macro uArrayRef.

```
template<typename> void print( uArrayRef( T, parm ) ) { // T & parm
    for ( size_t i = 0; i < parm.size(); i += 1 ) cout << *parm[i] << ' ';
    cout << endl;
}
print( sa ); // define << operator for S
```

- uArray can mimic unique_ptr for pointer types.

```
{
    uArray( S *, sap, size );
    for ( int i = 0; i < sap.size(); i += 1 ) {
        sap[i] = new S( i, i );
    }
    for ( int i = 0; i < sap.size(); i += 1 ) {
        cout << (*sap[i])->i << endl;
    }
} // delete array elements
```

```
{
    unique_ptr<S> sa[size];
    for ( int i = 0; i < size; i += 1 ) {
        sa[i] = make_unique<S>( i, i );
    }
    for ( int i = 0; i < size; i += 1 ) {
        cout << sa[i]->i << endl;
    }
} // delete array elements
```

  Note, uArray requires an explicit dereference of the pointer element, while unique_ptr does an implicitly dereferences.

4. When large local variables are allocated on a small stack.

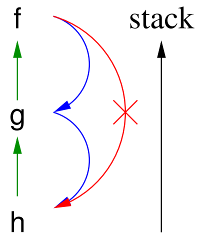
```
_Coroutine C {
    void main() {  // 64K stack
        S sa[100'000]; // overflow
        // initialize with assignment
        . . .
    } // implicitly array deallocate
};
```

```
_Coroutine C {
    void main() {
        uArrayPtr( S, sa, 100'000 )
        // initialize with ctor calls
        . . .
    } // implicitly array deallocate
};
```

- uArrayPtr or uArrayPtrFill dynamically allocate array in heap.
- Array implicitly freed at end of the containing block (like unique_ptr).
- Argument uArrayPtr is passed to a uArrayRef parameter (same as uArray).
- Alternatives are large stacks (waste virtual space, see 3.8) or dynamic stack growth (complex and pauses).

2 Nonlocal Transfer

- Routine **activation** (call/invocation) introduces complex control flow.
- ***Among*** routines, control flow is controlled by call/return mechanism.



  - routine h calls g calls f
  - cannot return from f to h, terminating g's activation

- **Modularization**: from software engineering, any contiguous code block can be factored into a (helper) routine and called in the program (modulo scoping rules).
- Modularization fails when refactoring exits, e.g., multi-level exits:

```
B1: for ( i = 0; i < 10; i += 1 ) {
        . . .
        B2: for ( j = 0; j < 10; j += 1 ) {
                . . .
                if ( . . . ) break B1;
                . . .
        }
        . . .
}
```

```
int rtn( . . . ) {
        B2: for ( j = 0; j < 10; j += 1 ) {
                . . .
                if ( . . . ) break B1;
                . . .
        }
}
B1: for ( i = 0; i < 10; i += 1 ) {
        . . . w = rtn( . . . ) . . .
}
```

Does this compile?

- Software pattern: many routines have **multiple outcomes**.
  - normal: return normal result and transfer after call
  - exceptional: return alternative result and **not** transfer after call
- **Nonlocal transfer** allows a routine to transfer back to its caller but **not** after the call.

```
C     Two alternate return parameters, denoted by * and implicitly named 1 and 2
            subroutine AltRet( c, *, * )
                integer c
                if ( c == 0 ) return          ! normal return
                if ( c == 1 ) return 1        ! alternate return
                if ( c == 2 ) return 2        ! alternate return
            end
```

```
C    Statements labelled 10 and 20 are alternate return points
           call AltRet( 0, *10, *20 )
           print *, "normal return 1"
           call AltRet( 1, *10, *20 )
           print *, "normal return 2"
           return
10         print *, "alternate return 1"
           call AltRet( 2, *10, *20 )
           print *, "normal return 3"
           return
20         print *, "alternate return 2"
           stop
           end
$ gfortran AltRtn.for
$ a.out
 normal return 1
 alternate return 1
 alternate return 2
```

- Generalization of multi-exit loop and multi-level exit.
  - Control structures ends normally or with an exceptional transfer.
- Pattern acknowledges:
  - algorithms have multiple outcomes
  - separating outcomes makes it easy to read and maintain a program
- **Pattern does not handle multiple levels of nested modularization.**
- If AltRet is further modularized, new routine has an alternate return to AltRet, which retains its alternate return to its caller.

```
C    Two alternate return parameters, denoted by * and implicitly named 1 and 2
           subroutine AltRet2( c, *, * )
               integer c
               if ( c == 0 ) return          ! normal return
               if ( c == 1 ) return 1        ! alternate return
               if ( c == 2 ) return 2        ! alternate return
               return 2
           end
C    Two alternate return parameters, denoted by * and implicitly named 1 and 2
           subroutine AltRet( c, *, * )
               integer c
               call AltRet2( c, *30, *40 )
               return
30             return 1
40             if ( c == 2 ) return 2            ! alternate return
           end
```

- Why not `call AltRet2( c, *10, *20 )`?

2.1 Traditional Approaches

- What are the traditional approaches for handling the multiple-outcome pattern?

- **return code**: returns value indicating normal or exceptional execution. e.g., printf() returns number of bytes transmitted or negative value.

- **status flag**: set shared (global) variable indicating normal or exceptional execution; the value remains as long as it is not overwritten. e.g., errno variable in UNIX.

- **fix-up routine**: a global and/or local routine called for an exceptional event to fix-up and return a corrective result so a computation can continue.

  ```
  int fixup( int i, int j ) { . . . } // local routine
  rtn( a, b, fixup ); // fixup called for exceptional event
  ```

  e.g., C++ has global routine-pointer new_handler called when **new** fails.

- Techniques are often combined, e.g.:

  ```
  if ( printf(. . .) < 0 ) {        // check return code for error
      perror( "printf:");           // errno describes specific error
      abort();                      // terminate program
  }
  ```

- **return union**: modern approach combining result/return-code and requiring return-code check on result access.

- **ALL** routines must return an appropriate union.

  ```
  optional< int * > Malloc( size_t size ) {
      if ( random() % 2 ) return (int *)malloc( sizeof( int ) );
      return nullopt;                         // no storage
  }
  optional< int > rtn( ) {
      optional< int * > p = Malloc( sizeof( int ) );
      if ( ! p ) return nullopt;              // malloc successful (true/false) ?
      **p = 7;      // compute
      if ( random() % 2 ) return **p;
      return nullopt;                         // bad computation
  }
  int main() {
      srandom( getpid() );
      optional< int > ret = rtn();
      if ( ret ) cout << *ret << endl;        // rtn successful?
      else cout << "no storage or bad computation" << endl;
  }
  $ repeat 5 a.out
  no storage or bad computation
  7
  no storage or bad computation
  7
  7
  ```

```
enum Alloc { NoStorage };
variant< int *, Alloc > Malloc( size_t size ) {
	if ( random() % 2 ) return (int *)malloc( sizeof( int ) );
	return NoStorage;
}
enum Comp { BadComp };
variant< int, Alloc, Comp > rtn( ) {
	variant< int *, Alloc > p = Malloc( sizeof( int ) );
	if ( ! holds_alternative<int *>(p) ) return NoStorage; // malloc successful ?
	*get<int *>(p) = 7;
	if ( random() % 2 ) return *get<int *>(p);
	return BadComp;
}
int main() {
	srandom( getpid() );
	variant< int, Alloc, Comp > ret = rtn();
	if ( holds_alternative<int>(ret) ) cout << get<int>(ret) << endl;
	else if ( holds_alternative<Comp>(ret) ) cout << "bad computation" << endl;
	else cout << "no storage" << endl;
}
$ repeat 5 a.out
no storage
bad computation
no storage
bad computation
7
```

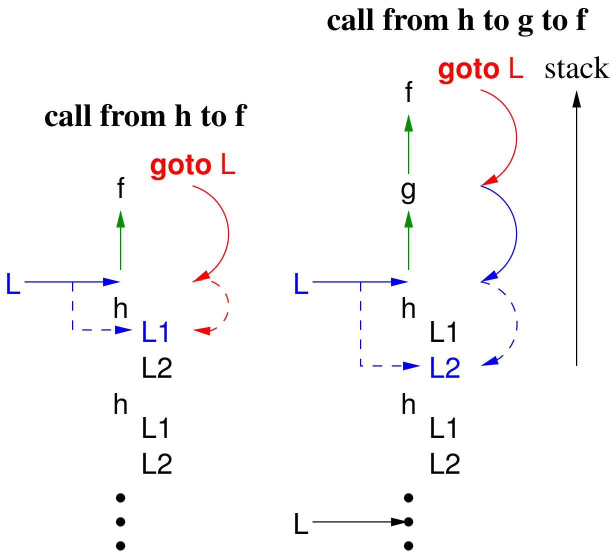
- Forces checking, unless explicitly access without `holds_alternative`.
- **Like Fortran, only returns one level.**
- Drawbacks of traditional techniques:
  - checking return code or status flag is optional ⇒ can be delayed or omitted, i.e., passive versus active
  - return code mixes exceptional and normal values ⇒ enlarges type or value range; normal/exceptional type/values should be independent
- Testing and handling of return code or status flag is often done locally (inline), otherwise information may be lost; but local testing/handling:
  - makes code difficult to read; each call results in multiple statements
  - can be inappropriate, e.g., library routines should **not terminate program**
- Nonlocal testing from nested routine calls is difficult as multiple codes are returned for analysis, compounding the mixing problem.
- Status flag can be overwritten before examined, and cannot be used in a concurrent environment because of sharing issues (e.g., save `errno`)
- Local fix-up routines increases the number of parameters.
  - increase cost of each call
  - must be passed through multiple levels enlarging parameter lists even when the fix-up routine is not used

- Nonlocal (global) fix-up routines, implemented with global routine pointer, have identical problems with status flags (e.g., new_handler).

2.2 Dynamic Multi-level Exit

- Rather than returning one level at a time, simpler for new modularized routine to bypass intermediate steps and transfer directly to original caller.
  - e.g., AltRet2 transfers directly to program main, instead of AltRet2 to AltRet to program main.
- **Dynamic multi-level exit** (DME) extend call/return semantics to transfer in the ***reverse*** direction to normal routine calls, requiring nonlocal transfer.

```
label L;
void f( int i ) {
    // nonlocal return
    if ( i == ... ) goto L;
}
void g( int i ) {
    if ( i > 1 ) { g( i - 1 ); return; }
    f( i );
}
void h( int i ) {
    if ( i > 1 ) { h( i - 1 ); return; }
    L = L1; // set dynamic transfer-point
    f( 1 ); goto S1;
  L1: // handle L1 nonlocal return
  S1: // continue normal execution
    L = L2; // set dynamic transfer-point
    g( 1 ); goto S2;
  L2: // handle L2 nonlocal return
  S2: // continue normal execution
}
```



- **label variable** contains:
  1. pointer to a block activation on the stack;
  2. transfer point within the block.
- Nonlocal transfer, **goto** L, is a two-step operation.
  1. direct control flow to the specified activation on the stack;
  2. then go to the transfer point (label constant) within the routine.
- Therefore, a label value is not statically/lexically determined.
  - recursion in g ⇒ unknown distance between f and h on stack.
  - what if L is set during the recursion of h?
- **This complexity is why label constants have local scope.**
- ***Transfer between goto and label value causes termination of stack block.***
- First, nonlocal transfer from f transfers to the label L1 in h's routine activation, terminating f's activation.

- Second, nonlocal transfer from `f` transfers to the static label `L2` in the stack frame for `h`, terminating the stack frame for `f` and `g`.

- Termination is implicit for direct transferring to `h` or requires stack unwinding if activations contain objects with destructors or finalizers.

- DME is possible in C using:
  - `jmp_buf` to declare a label variable,
  - `setjmp` to initialize a label variable,
  - `longjmp` to goto a label variable.

- DME allows multiple forms of returns to any level.
  - Normal return transfers to statement after the call, often implying completion of routine's algorithm.
  - Exceptional return transfers to statement **not** after the call, indicating an ancillary completion (but not necessarily an error).

- Unfortunately, nonlocal transfer is too general, allowing branching to almost anywhere, i.e., the goto problem.

- Simulate nonlocal transfer with return codes.

```
label L;
void f( int i, int j ) {

    for ( . . . ) {
        int k;
        . . .
  if ( i < j && k > i ) goto L;
        . . .
    }


}
void g( int i ) {

    for ( . . . ) {
        int j;
        . . . f( i, j ); . . .

    }


}
void h() {
    L = L1;
    for ( . . . ) {
        int i;
        . . . g( i ); . . .

    }
    . . .  return; // normal
    L1: . . . // exceptional
}
```

```
int f( int i, int j ) {
    bool flag = false;
    for ( ! flag && . . . ) {
        int k;
        . . .
  if ( i < j && k > i ) flag = true;
        else { . . . }
    }
    if ( ! flag ) { . . . }
    return flag ? –1 : 0;
}
int g( int i ) {
    bool flag = false;
    for ( ! flag && . . . ) {
        int j;
        . . . if ( f( i, j ) == –1 ) flag = true
        else { . . . }
    }
    if ( ! flag ) { . . . }
    return flag ? –1 : 0;
}
void h() {
    bool flag = false;
    for ( ! flag && . . . ) {
        int i;
        . . . if ( g( i ) == –1 ) flag = true;
        else { . . . }
    }
    if ( ! flag ) { . . . return; }
    . . .
}
```

2.3 Exception Handling

- DME, i.e., nonlocal transfer among routines, is often called **exception handling**.
- Exception handling is more than error handling.
- An **exceptional event** is an event that is (usually) known to exist but which is *ancillary* to an algorithm.
    - an exceptional event usually occurs with low frequency
    - e.g., division by zero, I/O failure, end of file, pop empty stack
- An **exception handling mechanism** (EHM) provides some or all of the alternate kinds of control-flow.
- Very difficult to simulate EHM with simpler control structures.
- Exceptions are supposed to make certain programming tasks easier, like robust programs.
- Robustness results because exceptions are active versus passive, forcing programs to react immediately when an exceptional event occurs.

- An EHM is not a panacea and only as good as the programmer using it.

2.4 Terminology

- **execution** is the language unit in which an exception can be raised, usually any entity with its own runtime stack.
- **exception type** is a type name representing an exceptional event.
- **exception** is an instance of an exception type, generated by executing an operation indicating an ancillary (exceptional) situation in execution.
- **raise** (**throw**) is the special operation that creates an exception.
- **source execution** is the execution raising an exception.
- **faulting execution** is the execution changing control flow due to a raised exception.
- **local exception** is when an exception is raised and handled by the same execution ⇒ source = faulting.
- **nonlocal exception** is when an exception is raised by a source execution but **delivered** to a different faulting execution ⇒ source ≠ faulting.
- **concurrent exception** is a nonlocal exception, where the source and faulting executions are executing concurrently.
- **propagation** directs control from a raise in the source execution to a handler in the faulting execution.
- **propagation mechanism** is the rules used to locate a handler.
  - most common propagation-mechanisms give precedence to handlers higher in the lexical/call stack
    - specificity versus generality
    - efficient linear search during propagation
- **handler** is inline (nested) routine responsible for handling raised exception.
  - handler **catch**es exception by **match**ing with one or more exception types
  - after catching, a handler executes like a normal subroutine
  - handler can return, reraise the current exception, or raise a new exception
  - **reraise** terminates current handling and continues propagation of caught exception.
    - useful if a handler cannot deal with an exception but needs to propagate same exception to handler further down the stack.
    - provided by a raise statement without an exception type:

      ```
      ... throw;     // no exception type
      ```

      where a raise must be in progress.
  - an exception is **handled** only if the handler returns rather than reraises
- **guarded block** is a language block with associated handlers, e.g., try-block in C++/Java.
- **unguarded block** is a block with no handlers.

- **termination** means control cannot return to the raise point.
  - all blocks on the faulting stack from the raise block to the guarded block handling the exception are terminated, called **stack unwinding**
- **resumption** means control returns to the raise point ⇒ no stack unwinding.
- EHM = Exception Type + Raise (exception) + Propagation + Handlers

2.5 Execution Environment

- The execution environment has a significant effect on an EHM.
- An object-oriented concurrent environment requires a more complex EHM than a non-object-oriented sequential environment.
- E.g., objects may have destructors that must be executed no matter how the object ends, i.e., by normal or exceptional termination.

```
class T {
    int *i;
    T() { i = new int[10]; ... }
    ~T() { delete [] i; ... } // must free storage
};
L: {
    T t; // constructor must be executed
    ... if ( ... ) break L;
    ...
} // destructor must be executed
```

- Control structures with **finally** clauses must always be executed (e.g., Java/μC++).

Java

```
L: try {
    infile = new Scanner( new File( "abc" ) );
    ... if ( ... ) break L;
    ...
} finally { // always executed
    infile.close(); // must close file

}
```

μC++

```
L: try {
    infile = new ifstream( "abc" );
    ... if ( ... ) break L; // alt 1
    ... // alt 2
} _Finally { // always executed
    infile.close();     // must close file
    delete infile;      // deallocate
}
```

- Hence, terminating a block complicates the EHM as object destructors (and recursively for nested objects) and **finally** clauses must be executed.
- For C++, a direct nonlocal transfer is often impossible, because of local objects with destructors, requiring linear stack unwinding.
- Also, complex execution-environment involving continuation, coroutine, task, each with its own execution stack.
- Given multiple stacks, an EHM can be more sophisticated, resulting in more complexity.
  - e.g., if no handler found in one stack, continue propagating exception in another stack.

2.6 Implementation

- DME is *limited* in most programming languages using exception handling.

```
struct E {};  // label
void f(. . .) {
    . . .
    if ( . . . ) throw E(); // raise
    . . .
}
int main() {
    try {
        f(. . .);
    } catch( E ) {. . .} // handler 1
    try {
        f(. . .);
    } catch( E ) {. . .} // handler 2
    . . .
}
```

```
label L;
void f(. . .) {
    . . .
    if ( . . . ) goto L;
    . . .
}
int main() {
    L = L1; // set transfer-point
    f(. . .); goto S1;
  L1:  // handle nonlocal return
  S1: L = L2; // set transfer-point
    f(. . .); goto S2;
  L2:  // handle nonlocal return
  S2: ; . . .
}
```

- To implement throw/catch, the throw must know the last guarded block with a handler for the raised exception type.
- One approach is to:
  - associate a label variable with each exception type
  - set label variable on entry to each guarded block with handler for the type
  - reset label variable on exit to previous value, i.e., previous guarded block for that type
- However, setting/resetting label variable on **try** block entry/exit has a cost (small).
  - rtn called million times but exception E never raised ⇒ million unnecessary operations.

```
void rtn( int i ) {
    try {                    // set label on entry
        . . .
    } catch( E ) { . . . }   // reset label on exit
}
```

  - Instead, **catch**/destructor data is stored once externally for each block and handler found by linear search during a stack walk (no direct transfer).
  - Advantage, millions of **try** entry/exit, but only tens of exceptions raised.
- Hence, termination is often implemented using zero cost on guarded-block entry but an expensive approach on raise.

2.7 Static/Dynamic Call/Return

- All routine/exceptional control-flow can be characterized by two properties:
  1. static/dynamic call: routine/exception name at the call/raise is looked up statically (compile-time) or dynamically (runtime).
  2. static/dynamic return: after a routine/handler completes, it returns to its static (definition) or dynamic (call) context.

	call/raise	
return/handled	static	dynamic
static	1) sequel	3) termination exception
dynamic	2) routine	4) routine pointer, virtual routine, resumption

- E.g., case 2) is a normal routine, with static name lookup at the call and a dynamic return.

2.8 Static Propagation (Sequel)

- Case 1) is called a **sequel**, which is a routine with no return value, where:
  - the sequel name is looked up lexically at the call site, but
  - control returns to the end of the block in which the sequel is declared.

```
A: for ( ;; ) {


    B: for ( ;; ) {

        C: for ( ;; ) {
                . . .
            if ( . . . ) { break A; }
                . . .
            if ( . . . ) { break B; }
                . . .
            if ( . . . ) { break C; }
                . . .
        }
    }
}
```

```
for ( ;; ) {
    sequel S1( . . . ) { . . . } // nested
    void M1( . . . ) { . . . if ( . . . ) S1( . . . ); . . . }
    for ( ;; ) {
        sequel S2( . . . ) { . . . } // nested
        C: for ( ;; ) {

              M1( . . . ); // modularize

            if ( . . . ) S2( . . . ); // modularize
              . . .
            if ( . . . ) break C;
              . . .
        }
    } // S2 static return
} // S1 static return
```

- Without a sequel, it is impossible to modularize code with static exits.
- ⇒ propagation is along the lexical structure
- Adheres to the termination model, as the stack is unwound.
- Sequel handles termination for a *non-recoverable* event (simple exception handling).

```
{ // new block
    sequel StackOverflow(. . .) { . . . } // handler
    class stack {
        void push( int i ) {
            if (. . .) StackOverflow(. . .); // 2nd outcome
        } // 1st outcome
        . . .
    };
    stack s;
    . . . s.push( 3 ); . . . // overflow ?
} // sequel returns here
```

- The advantage of the sequel is the handler is statically known (like static multi-level exit), and can be as efficient as a direct transfer.

- The disadvantage is that the sequel only works for monolithic programs because it must be statically nested at the point of use.
  - Fails for modular (library) code as the static context of the module and user code are disjoint.
  - E.g., if `stack` is separately compiled, the sequel call in `push` no longer knows the static blocks containing calls to it.

2.9 Dynamic Propagation

- Cases 3) and 4) are called termination and resumption, and both have dynamic raise with static/dynamic return, respectively.

- Dynamic propagation/static return (case 3) is also called dynamic multi-level exit (see Section 2.2, p. 11).

- The advantage is that dynamic propagation works for separately-compiled programs.

- The disadvantage (advantage) of dynamic propagation is the handler is not statically known.
  - without dynamic handler selection, the same action and context for that action is executed for every exceptional change in control flow.

2.9.1 Termination

- For termination:
  - control transfers from the start of propagation to a handler ⇒ dynamic raise (call)
  - when handler returns, it performs a static return ⇒ stack is unwound (like sequel)

- There are 2 basic termination forms for a *non-recoverable* operation: terminate and retry.

- **terminate** provides *limited* mechanism for block transfer on the call stack, like labelled **break**.

```
struct E {};  // label
void f(. . .) {
    . . .
    if ( . . . ) throw E(); // raise
    . . .
}
int main() {
    try {
        f(. . .);
    } catch( E ) {. . .} // handler 1
    try {
        f(. . .);
    } catch( E ) {. . .} // handler 2
    . . .
}
```

- No intermediate code to forward alternative outcome (see return union examples page 9).

```
struct NoStorage {};
struct BadComp {};
int * Malloc( size_t size ) {
     if ( random() % 2 ) return (int *)malloc( sizeof( int ) );
     throw NoStorage();
}
int rtn( ) {
     int * p = Malloc( sizeof( int ) );
     // DO NOT HAVE TO FORWARD NoStorage
     *p = 7; // compute
     if ( random() % 2 ) return *p;
     throw BadComp();
}
int main() {
     srandom( getpid() );
     try { cout << rtn() << endl; }
     catch( BadComp ) { cout << "bad computation" << endl; }
     catch( NoStorage ) { cout << "no storage" << endl; }
}
```

- C++ I/O can be toggled to raise exceptions versus return codes (like μC++).

C++

```
ifstream infile;
ofstream outfile;
outfile.exceptions( ios_base::failbit );
infile.exceptions( ios_base::failbit );
switch ( argc ) {
  case 3:
     try {
          outfile.open( argv[2] );
     } catch( ios_base::failure & ) {...}
     // fall through to handle input file
  case 2:
     try {
          infile.open( argv[1] );
     } catch( ios_base::failure & ) {...}
     break;
  default:
     . . .
} // switch
string line;
try {
     for ( ;; ) {  // loop until end-of-file
          getline( infile, line );
          outfile << line << endl;
     }
} catch( ios_base::failure & ) {}
```

μC++

```
ifstream infile;
ofstream outfile;


switch ( argc ) {
  case 3:
     try {
          outfile.open( argv[2] );
     } catch( uFile::Failure & ) {...}
     // fall through to handle input file
  case 2:
     try {
          infile.open( argv[1] );
     } catch( uFile::Failure & ) {...}
     break;
  default:
     . . .
} // switch
string line;

for ( ;; ) {
     getline( infile, line );
  if ( infile.fail() ) break; // no eof exception
     outfile << line << endl;
}
```

- ios::exception mask indicates stream state-flags throw an exception if set
- failure exception raised after failed open or end-of-file when failbit set in exception mask
- μC++ provides exceptions for I/O errors, but no exception for eof.

- μC++ also provides **bound catch clause**, where catch depends on the object raising exception.

```
_Exception E {};
struct Obj {
    void mem() { . . . _Throw E{}; . . . } // implicitly store 'this' into exception
};
int main() {
    Obj obj1, obj2;
    try {
        . . . obj1.mem(); . . . obj2.mem(); . . . _Throw E{};
    } catch( obj1.E ) {                    // only handle E from obj1 exception
    } catch( obj2.E ) {                    // only handle E from obj2 exception
    } catch( E ) {                         // handle any E exception
    }
}
```

- Better separation of alternate outcomes without flag variables.

```
#include <fstream>
istream * infile = &cin;                          // default value
ostream * outfile = &cout;                        // default value
try {
    switch ( argc ) {
      case 3: case 2:
        // open input file first as output creates file
        infile = new ifstream();
        dynamic_cast<ifstream *>(infile)->open( argv[3] );
        if ( argc == 3 ) {
            outfile = new ofstream();
            dynamic_cast<ofstream *>(outfile)->open( argv[4] );
        } // if
        // FALL THROUGH
      case 1:                                     // defaults
        break;
      default:                                    // wrong number of options
        // error
    } // switch
} catch( *infile.uFile::Failure & ) {             // input open failed
    cerr << "Error! Could not open input file \"" << argv[3] << "\"" << endl;
    exit( EXIT_FAILURE );                         // TERMINATE
} catch( *outfile.uFile::Failure & ) {            // output open failed
    cerr << "Error! Could not open output file \"" << argv[4] << "\"" << endl;
    exit( EXIT_FAILURE );                         // TERMINATE
} // try
```

- Why separate declaration and open versus `infile = new ifstream( argv[3] )`?

- Why is dynamic cast necessary for open?

- **retry** is a combination of termination with special handler semantics, i.e., restart the guarded block handling the exception (Eiffel). (Pretend end-of-file is an exception of type Eof.)

Retry

```
char readfiles( char *files[], int N ) {
    int i = 0, value;
    ifstream infile;
    infile.open( files[i] );

    try {
        ... infile >> value; ...
    } retry( Eof ) {
        i += 1;
        infile.close();
      if ( i == N ) goto Finished;
        infile.open( files[i] );
    }
  Finished: ;
}
```

Simulation

```
char readfiles( char *files[], int N ) {
    int i = 0, value;
    ifstream infile;
    infile.open( files[i] );
    while ( true ) {
        try {
            ... infile >> value; ...
        } catch( eof ) {
            i += 1;
            infile.close();
          if ( i == N ) break;
            infile.open( files[i] );
        }
    }
}
```

- Because retry can be easily simulated, it is seldom supported directly.

2.9.2 Resumption

- **Resumption** provides a *limited* mechanism to generate new blocks on the call stack:
  - control transfers from the start of propagation to a handler ⇒ dynamic raise (call)
  - when handler returns, it is dynamic return ⇒ stack is NOT unwound (like routine)
- A resumption handler is a corrective action so a computation can continue.

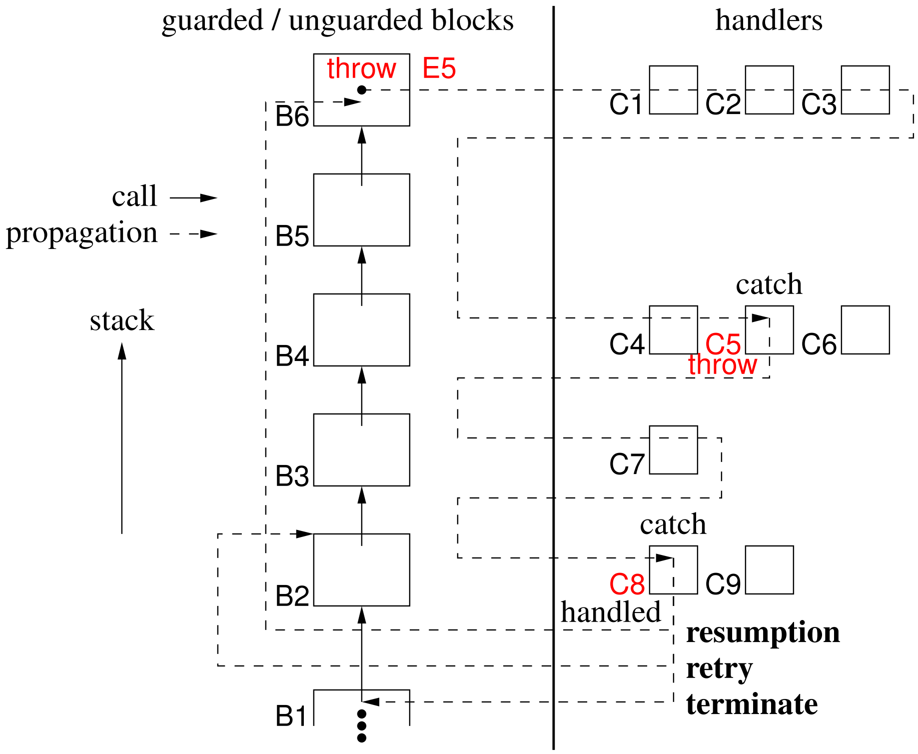
```
void f( ..., /* no fixups */ ) {
    if ( ... ) resume E();
    // control returns here
}
int main() {
    try {
        f( ... ); // no fixups
    } catch( E ) {
        // handler 1
    }
    try {
        f( ... ); // no fixups
    } catch( E ) {
        // handler 2
    }
}
```

```
void f( ..., void (*fixup)( ... ) ) {
    if ( ... ) fixup( ... );
    // control returns here
}
void fixup1( ... ) {
    // handler 1
}
void fixup2( ... ) {
    // handler 2
}
int main() {
    f( ..., fixup1 );
    f( ..., fixup2 );
}
```

- No intermediate code to forward fixup down to raise point.

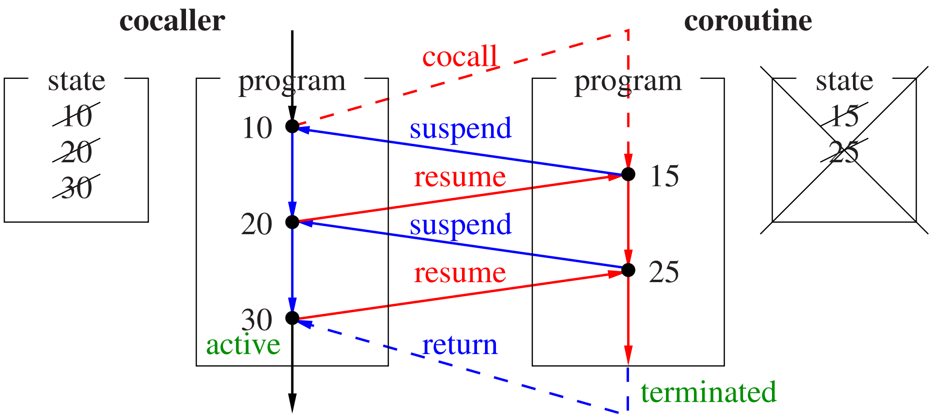
2.10 Exceptional Example

```
B1  {
B2      try {
B3          try {
B4              try {
B5                  {
B6                      try {
                            . . . throw E5(); . . .
C1                      } catch( E7 ) { . . . }
C2                        catch( E8 ) { . . . }
C3                        catch( E9 ) { . . . }
                    }
C4              } catch( E4 ) { . . . }
C5                catch( E5 ) { . . . throw; . . . }
C6                catch( E6 ) { . . . }
C7          } catch( E3 ) { . . . }
C8      } catch( E5 ) { . . . resume/retry/terminate }
C9        catch( E2 ) { . . . }
    }
```



3 Coroutine

- A **coroutine** is a routine that can also be suspended at some point and resumed from that point when control returns.
- The state of a coroutine consists of:
  - an **execution location**, starting at the beginning of the coroutine and remembered at each suspend.
  - an **execution state** holding the data created by the code the coroutine is executing. ⇒ each coroutine has its own stack, containing its local variables and those of any routines it calls.
  - an **execution status**—**active** or **inactive** or **terminated**—which changes as control resumes and suspends in a coroutine.
- Hence, a coroutine does not start from the beginning on each activation; it is activated at the point of last suspension.
- In contrast, a routine always starts execution at the beginning and its local variables only persist for a single activation.



- A coroutine handles the class of problems that need to retain state between calls (e.g. plugin, device driver, finite-state machine).
- A coroutine executes synchronously with other coroutines; hence, no concurrency among coroutines.
- Coroutines are the precursor to concurrent tasks, and introduce the complex concept of suspending and resuming on separate stacks.
- Two different approaches are possible for activating another coroutine:
  1. A **semi-coroutine** acts asymmetrically, like non-recursive routines, by implicitly reactivating the coroutine that previously activated it.
  2. A **full coroutine** acts symmetrically, like recursive routines, by explicitly activating a member of another coroutine, which directly or indirectly reactivates the original coroutine (activation cycle).
- These approaches accommodate two different styles of coroutine usage.

3.1 Semi-Coroutine

3.1.1 Fibonacci Sequence

$$f(n) = \begin{cases} 0 & n = 0 \\ 1 & n = 1 \\ f(n-1) + f(n-2) & n \geq 2 \end{cases}$$

- 3 states, producing unbounded sequence: 0, 1, 1, 2, 3, 5, 8, 13, 21, ...

3.1.1.1 Direct

- Compute and print Fibonacci numbers.

```
int main() {
    int fn, fn1, fn2;
    fn = 0;  fn1 = fn;                 // 1st case
    cout << fn << endl;
    fn = 1;  fn2 = fn1;  fn1 = fn;     // 2nd case
    cout << fn << endl;
    for ( ;; ) {                       // infinite loop
        fn = fn1 + fn2;  fn2 = fn1;  fn1 = fn; // general case
        cout << fn << endl;
    }
}
```

- Convert to routine that generates a sequence of Fibonacci numbers on each call (no output):

```
int main() {
    for ( int i = 1; i <= 10; i += 1 ) { // first 10 Fibonacci numbers
        cout << fibonacci() << endl;
    }
}
```

- Examine different solutions.

3.1.1.2 Routine

```
int fn1, fn2, state = 1; // global variables
int fibonacci() {
    int fn;
    switch ( state ) {
      case 1:
        fn = 0;  fn1 = fn;  state = 2;
        break;
      case 2:
        fn = 1;  fn2 = fn1;  fn1 = fn;  state = 3;
        break;
      case 3:
        fn = fn1 + fn2;  fn2 = fn1;  fn1 = fn;
        break;
    }
    return fn;
}
```

- unencapsulated global variables necessary to retain state between calls
- only one fibonacci generator can run at a time
- execution state must be explicitly retained

```
#define FIB_INIT { 0, 1 }           /* first two Fibonacci numbers */
struct Fibonacci { int fn2, fn1; };
int fib( Fibonacci & f ) {
    int ret = f.fn2;
    int fn = f.fn1 + f.fn2;         // only last state (3) in Fibonacci definition
    f.fn2 = f.fn1; f.fn1 = fn;
    return ret;
}
int main() {
    Fibonacci f1 = FIB_INIT, f2 = FIB_INIT;  // multiple instances
    for ( int i = 1; i <= 10; i += 1 ) {
        cout << fib( f1 ) << " " << fib( f2 ) << endl;
    }
}
```

- unencapsulated program global variables become encapsulated structure variables
- multiple fibonacci generators (objects) can run at a time
- execution state removed by precomputing first 2 Fibonacci numbers and returning $f(n-2)$

3.1.1.3 Class

```
class Fibonacci {
    int fn, fn1, fn2, state = 1; // global class variables
  public:
    int operator()() {          // functor
        switch ( state ) {
          case 1:
            fn = 0;  fn1 = fn;  state = 2;
            break;
          case 2:
            fn = 1;  fn2 = fn1;  fn1 = fn;  state = 3;
            break;
          case 3:
            fn = fn1 + fn2;  fn2 = fn1;  fn1 = fn;
            break;
        }
        return fn;
    }
};
int main() {
    Fibonacci f1, f2;  // multiple instances
    for ( int i = 1; i <= 10; i += 1 ) {
        cout << f1() << " " << f2() << endl;
    } // for
}
```

- unencapsulated program global variables become encapsulated object global variables
- multiple fibonacci generators (objects) can run at a time

- execution state still explicit or use initialization trick

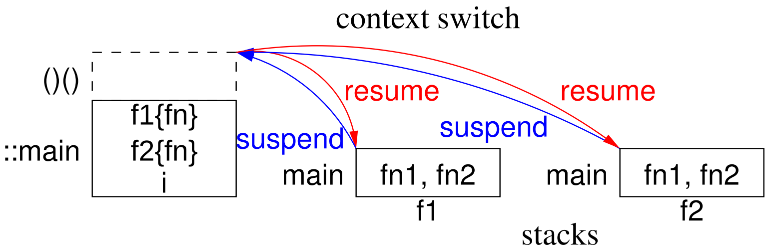
3.1.1.4 Coroutine

```
_Coroutine Fibonacci {    // : public uBaseCoroutine
    int fn;               // used for communication
    void main() {         // distinguished member
        int fn1, fn2;     // retained between resumes
        fn = 0;  fn1 = fn;
        suspend();        // return to last resume
        fn = 1;  fn2 = fn1;  fn1 = fn;
        suspend();        // return to last resume
        for ( ;; ) {
            fn = fn1 + fn2;  fn2 = fn1;  fn1 = fn;
            suspend();    // return to last resume
        }
    }
  public:
    int operator()() {    // functor
        resume();         // transfer to last suspend
        return fn;
    }
};

int main() {
    Fibonacci f1, f2;     // multiple instances
    for ( int i = 1; i <= 10; i += 1 ) {
        cout << f1() << " " << f2() << endl;
    }
}
```

- **no explicit execution state!** (see direct solution)
- **_Coroutine** type wraps coroutine and provides *all* **class** properties
- distinguished member main (coroutine main) can be suspended and resumed
- no parameters or return value (supplied by **public** members and communication variables).
- coroutine main should be a **private/protected** member. Why?
- **compile with u++ command**
- All coroutines inherit from base type uBaseCoroutine:

```
class uBaseCoroutine {
  protected:
    void resume();                    // context switch to this
    void suspend();                   // context switch to last resumer
    virtual void main() = 0;          // starting routine for coroutine
  public:
    uBaseCoroutine();
    uBaseCoroutine( unsigned int stackSize ); // set stack size
    void verify();                    // check stack
    const char * setName( const char * name ); // printed in error messages
    const char * getName() const;
    uBaseCoroutine & starter() const; // coroutine performing first resume
    uBaseCoroutine & resumer() const; // coroutine performing last resume
};
```

- Program main called from hidden coroutine ⇒ **has coroutine properties**.
- resume/suspend cause a **context switch** between coroutine stacks



- first resume starts main on new stack (cocall); subsequent resumes reactivate last suspend.
- suspend reactivates last resume
- object becomes a coroutine on first resume; coroutine becomes an object when main ends
- routine frame at the top of the stack *knows* where to activate execution
- suspend/resume are **protected** members to prevent external calls. Why?
- Coroutine main does not have to return before a coroutine object is deleted.
- When deleted, a coroutine's stack is always unwound and any destructors executed. Why?
- **Warning, do not use catch(. . .) (catch any) in a coroutine, if it can be deleted before terminating, as a cleanup exception is raised to force stack unwinding (implementation issue).**

3.1.2 Format Output

Unstructured input:

```
abcdefghijklmnopqrstuvwxyzabcdefghijklmnopqrstuvwxyz
```

Structured output:

```
abcd  efgh  ijkl  mnop  qrst
uvwx  yzab  cdef  ghij  klmn
opqr  stuv  wxyz
```

blocks of 4 letters, separated by 2 spaces, grouped into lines of 5 blocks.

3.1.2.1 Direct

- Read characters and print formatted output.

```
int main() {
    int g, b;
    char ch;
    cin >> noskipws;                        // turn off white space skipping
    eof: for ( ;; ) {                       // for as many characters
        for ( g = 0; g < 5; g += 1 ) {      // groups of 5 blocks
            for ( b = 0; b < 4; b += 1 ) {  // blocks of 4 chars
                for ( ;; ) {                // for newline characters
                    cin >> ch;              // read one character
      if ( cin.fail() ) break eof;          // eof ? multi-level exit
                  if ( ch != '\n' ) break;  // ignore newline
                }
                cout << ch;                 // print character
            }
            cout << "  ";                   // print block separator
        }
        cout << endl;                       // print group separator
    }
    if ( g != 0 || b != 0 ) cout << endl; // special case
}
```

- Convert to routine passed one character at a time to generate structured output (no input).

3.1.2.2 Routine

```
int g, b;                           // global variables
void fmtLines( char ch ) {
    if ( ch != -1 ) {               // not EOF ?
        if ( ch == '\n' ) return;   // ignore newline
        cout << ch;                 // print character
        b += 1;

        if ( b == 4 ) {             // block of 4 chars
            cout << "  ";           // block separator
            b = 0;
            g += 1;
        }

        if ( g == 5 ) {             // group of 5 blocks
            cout << endl;           // group separator
            g = 0;
        }
    } else {
        if ( g != 0 || b != 0 ) cout << endl; // special case
    }
}
```

```
int main() {
    char ch;
    cin >> noskipws;              // turn off white space skipping
    eof: for ( ;; ) {             // for as many characters
        cin >> ch;
      if ( cin.fail() ) break eof;    // eof ?
        fmtLines( ch );
    }
    fmtLines( -1 );               // indicate EOF
}
```

- must retain variables b and g between successive calls.
- only one instance of formatter
- linearize (flatten) loops: one loop, lots of **if** statements

3.1.2.3 Class

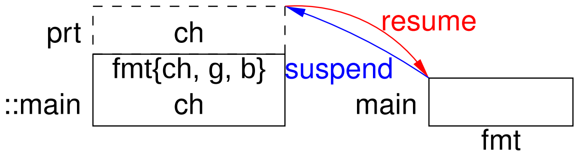
```
class Format {
    int g, b;                     // global class variables
  public:
    Format() : g( 0 ), b( 0 ) {}
    ~Format() { if ( g != 0 || b != 0 ) cout << endl; }
    void prt( char ch ) {
      if ( ch == '\n' ) return;   // ignore newline
        cout << ch;               // print character
        b += 1;
        if ( b == 4 ) {           // block of 4 chars
            cout << "  ";         // block separator
            b = 0;
            g += 1;
        }
        if ( g == 5 ) {           // group of 5 blocks
            cout << endl;         // group separator
            g = 0;
        }
    }
};
int main() {
    Format fmt;
    char ch;
    cin >> noskipws;              // turn off white space skipping
    eof: for ( ;; ) {             // for as many characters
        cin >> ch;                // read one character
      if ( cin.fail() ) break eof;    // eof ?
        fmt.prt( ch );
    }
}
```

- Solves encapsulation and multiple instances issues, but explicitly managing execution state.

3.1.2.4 Coroutine

```
_Coroutine Format {
    char ch;                        // used for communication
    int g, b;                       // global because used in destructor
    void main() {
        for ( ;; ) {                        // for as many characters
            for ( g = 0; g < 5; g += 1 ) { // groups of 5 blocks
                for ( b = 0; b < 4; b += 1 ) { // blocks of 4 characters
                    for ( ;; ) {            // for newline characters
                        suspend();
                      if ( ch != '\n' ) break; // ignore newline
                    }
                    cout << ch;             // print character
                }
                cout << "  ";               // print block separator
            }
            cout << endl;                   // print group separator
        }
    }
  public:
    Format() { resume(); }          // start coroutine
    ~Format() { if ( g != 0 || b != 0 ) cout << endl; }
    void prt( char ch ) { Format::ch = ch; resume(); }
};
int main() {
    Format fmt;
    char ch;
    cin >> noskipws;                // turn off white space skipping
    for ( ;; ) {
        cin >> ch;                  // read one character
      if ( cin.fail() ) break;      // eof ?
        fmt.prt( ch );
    }
}
```

- resume in constructor allows coroutine main to get to 1st input suspend.



3.1.3 Correct Coroutine Usage

- **Eliminate computation or flag variables retaining information about execution state.**
- E.g., sum even and odd digits of 10-digit number, where each digit is passed to coroutine:

BAD: Explicit Execution State

```
for ( int i = 0; i < 10; i += 1 ) {
    if ( i % 2 == 0 ) // even ?
        even += digit;
    else
        odd += digit;
    suspend();
}
```

GOOD: Implicit Execution State

```
for ( int i = 0; i < 5; i += 1 ) {

    even += digit;
    suspend();
    odd += digit;
    suspend();
}
```

- Right example illustrates coroutine “Zen”; let it do the work.
- E.g., a BAD solution for the previous Fibonacci generator is:

```
void main() {
    int fn1, fn2, state = 1;
    for ( ;; ) {
        switch ( state ) {  // no Zen
          case 1:
            fn = 0;  fn1 = fn;  state = 2;
            break;
          case 2:
            fn = 1;  fn2 = fn1;  fn1 = fn;  state = 3;
            break;
          case 3:
            fn = fn1 + fn2;  fn2 = fn1;  fn1 = fn;
            break;
        }
        suspend();                   // no Zen
    }
}
```

- Coroutine’s capabilities not used:
  - explicit flag variable controls execution state
  - original program structure lost in **switch** statement
- Must do more than just *activate* coroutine main to demonstrate understanding of retaining data and execution state within a coroutine.

3.1.4 Coroutine Construction

- Fibonacci and formatter coroutines express original algorithm structure (no restructuring).
- When possible, simplest coroutine construction is to write a direct (stand-alone) program.
- Convert to coroutine by:
  - putting processing code into coroutine main,
  - converting reads if program is consuming or writes if program is producing to suspend,
    - Fibonacci consumes nothing and produces (generates) Fibonacci numbers ⇒ convert writes (cout) to suspends.
    - Formatter consumes characters and only indirectly produces output (as side-effect) ⇒ convert reads (cin) to suspends.
  - use interface members and communication variables to transfer data in/out of coroutine.

- This approach is impossible for advanced coroutine problems.

3.2 μC++ EHM

The following features characterize the μC++ EHM:

- exceptions must be generated from a specific kind of type.
- supports two kinds of raising: throw and resuming.
- supports two kinds of handlers, termination and resumption, matching with the kind of raise.
- supports propagation of nonlocal and concurrent exceptions.
- all exception types (user, runtime, and I/O) are grouped into a hierarchy.

3.3 Exception Type

- C++ allows any type to be used as an exception type.
- μC++ restricts exception types to those types defined by **_Exception**.

```
_Exception exception-type-name { ... };
```

- An exception type has all the properties of a **class**.
- Every exception type must have a public default and copy constructor.
- An exception is the same as a class-object with respect to creation and destruction.

```
_Exception D { ... };
D d;                // local creation
_Resume d;
D * dp = new D;     // dynamic creation
_Resume *dp;
delete dp;
_Throw D();         // temporary local creation
```

3.4 Inherited Members

- Each exception type inherits the following members from uBaseException:

```
class uBaseException {  // like std::exception
    uBaseException( const char * const msg = "" );
    const char * const message() const; // C++ std::exception::what
    const uBaseCoroutine & source() const;
    const char * sourceName() const;
    virtual void defaultTerminate();
    virtual void defaultResume();
};
```

- `uBaseException( const char * const msg = "" )` – msg is printed if the exception is not caught.
    - Message string is copied so it is safe to use within an exception even if the context of the raise is deleted.
- message returns the string message associated with an exception.
- source returns the coroutine/task that raised the exception.

  - coroutine/task may be deleted when the exception is caught so this reference may be undefined.
- sourceName returns the name of the coroutine/task that raised the exception.
  - name is copied from the raising coroutine/task when exception is created.
- defaultTerminate is implicitly called if an exception is thrown but not handled.
  - default action is to forward an UnhandledException exception to resumer/joiner.
- defaultResume is implicitly called if an exception is resumed but not handled.
  - default action is to throw the exception.

3.5 Raising

- There are two raising mechanisms: throwing and resuming.

```
_Throw [ exception-type ] ;
_Resume [ exception-type ]  [ _At uBaseCoroutine-id ] ;
```

- If **_Throw** has no *exception-type*, it is a rethrow.
- If **_Resume** has no *exception-type*, it is a reresume.
- The optional **_At** clause allows the specified exception or the currently propagating exception to be raised at another coroutine or task.
- Nonlocal/concurrent raise restricted to resumption as raising execution-state is often unaware of the handling execution-state.
- Resumption allows faulting execution greatest flexibility: it can process the exception as a resumption or rethrow the exception for termination.
- Exceptions in μC++ are propagated differently from C++.

C++

```
class B {};
class D : public B {};
void f( B & t ) { ... throw t; ... }
try {
    D m;
    f( m );
} catch( D & ) { cout << "D" << endl; }
  catch( B & ) { cout << "B" << endl; }
```

μC++

```
_Exception B {};
_Exception D : public B {};
void f( B & t ) { ... _Throw t; ...}
try {
    D m;
    f( m );
} catch( D & ) { cout << "D" << endl; }
  catch( B & ) { cout << "B" << endl; }
```

  - In C++, f is passed an object of derived type D but throws an object of base type B.
  - In μC++, f is passed an object of derived type D and throws the original object of type D.
  - This change allows handlers to catch the specific (derived) rather than the general (base) exception-type.

3.6 Handler

- μC++ has two kinds of handlers, termination and resumption, which match with the kind of raise.

3.6.1 Termination

- The μC++ termination handler is the **catch** clause of a **try** block, i.e., same as in C++.

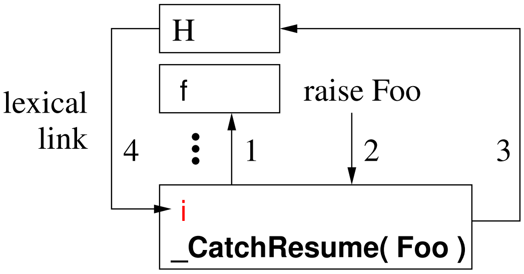
3.6.2 Resumption

- μC++ extends the **try** block to include resumption handlers.
- Resumption handler is denoted by a **_CatchResume** clause after **try** body:

```
try {
        . . .
}       _CatchResume( E1 ) { . . . }   // must appear before catch clauses
        // more _CatchResume clauses
        _CatchResume( . . . ) { . . . }  // must be last _CatchResume clause
        catch( E2 ) { . . . }            // must appear after _CatchResume clauses
        // more catch clauses
        catch( . . . ) { . . . }         // must be last catch clause
```

- Any number of resumption handlers can be associated with a **try** block.
- All **_CatchResume** handlers must precede any **catch** handlers, solely to make reading the two sets of clauses easier.
- Like **catch**(. . .) (catch-any), **_CatchResume**(. . .) must appear at the end of the list of the resumption handlers.
- Resumption handler can access types and variables visible in its local scope.

```
typedef int Foo;
Foo i;
try {
        f(. . .)                    // f is recursive and raises Foo
} _CatchResume( Foo & e ) { // handler H
        Foo fix = i;                // use type and variable in local scope
        . . .  e = fix . . .        // change _Resume block
}
```



1. call f
2. propagation from f to handler H
3. call handler
4. dereference lexical link to i

- **lexical link** is like **this** but to declaration block rather than object (lambda capture [&]).
- ***Resumption handler cannot perform a* break*,* continue*,* goto*, or* return*.***
  - Resumption handler is corrective action so computation can continue.
  - If correction impossible, handler should **throw** an exception not step into an enclosing block to cause the stack to unwind.

```
B: try {
      f();                         // recursive calls and _Resume E()
   } _CatchResume( E e ) {         // handler H
      . . . break B;               // force static return (disallowed)
      _Throw e;                    // force recovery (allowed)
   }
```

- ○ Assume **try** body makes recursive calls to f, so **break** must unwind stack to transfer into stack frame B (nonlocal transfer).
- ○ Throw may find another recovery action closer to raise point than B that can deal with the problem.

3.6.3 Termination/Resumption

- The raise dictates set of handlers examined during propagation:
  - ○ terminating propagation (**_Throw**) only examines termination handlers (**catch**),
  - ○ resuming propagation (**_Resume**) only examines resumption handlers (**_CatchResume**).
- Exception types in each set can overlap.

```
_Exception E {};
void rtn() {
      try {
            _Resume E();
      } _CatchResume( E & e ) { . . . _Throw e; }     // H1
        catch( E & e ) { . . . }                       // H2
}
```

- Resumption handler H1 is invoked by the resume in the **try** block generating call stack:

  rtn → **try**{}**_CatchResume(E)**, **catch**(E)→ H1

- Handler H1 throws E and the stack is unwound until the exception is caught by termination-handler **catch**(E) and handler H2 is invoked.

  rtn → H2

- The termination handler is available as resuming does not unwind the stack.
- Note interaction between resuming, defaultResume, and throwing:

```
_Exception R {};
void rtn() {
      try {
            _Resume R();           // resume not throw
      } catch( R & ) { . . . }     // H1, no _CatchResume!!!
}
```

- This generates the following call stack as there is no eligible resumption handler (or there is a handler but marked ineligible):

  rtn → **try**{}**catch(R)** → defaultResume

- ***When* defaultResume *is called, the default action throws* R** (see Section 3.4, p. 32).

  rtn → H1

- Then termination propagation unwinds the stack until the matching **catch** clause of the **try** block.

3.6.4 Object Binding

- **_Resume**/**_Throw** implicitly store the **this** associated with the member raising an exception.
- For a static member or free routine, there is no binding (no **this**).
- For non-local raise, the binding is the coroutine/task object executing the raise.

3.6.5 Bound Handlers

- **catch** / **_CatchResume** provide object-specific matching.

```
catch(   raising-object . exception-declaration ) { ... }
_CatchResume(   raising-object . exception-declaration ) { ... }
```

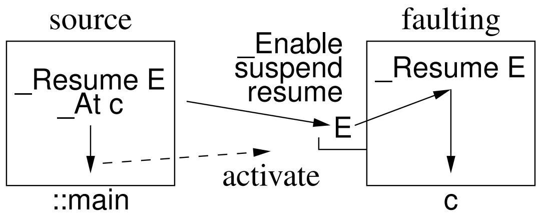
- The "catch-any" handler, "...", does not have a bound form.
- An exception is caught when the bound and handler objects are equal, and the raised exception equals the handler exception or its base-type.

3.7 Nonlocal Exceptions

- Nonlocal exceptions are exceptions raised by a source execution at a faulting execution.
- Nonlocal exceptions are possible because each coroutine (execution) has its own stack.
- Nonlocal exceptions are raised using **_Resume** ... **_At** ....

```
_Exception E {};
_Coroutine C {
    void main() {
        // initialization, no nonlocal delivery
        try {                           // setup handlers
            _Enable {                   // allow nonlocal exceptions
                ... suspend(); ...      // inside suspend is _Resume E();
            }                           // disable all nonlocal exceptions
        } _CatchResume( E ) { ...       // option 1: continue after suspend
        } catch( E ) { ...              // option 2: continue after try
        }
        // finalization, no nonlocal delivery
    }
  public:
    C() { resume(); }                   // prime try (not always possible)
    void mem() { resume(); }
};
int main() {
    C c;
    _Resume E() _At c;                  // exception pending
    c.mem();                            // trigger exception
}
```

- For nonlocal resumption, **_Resume** is a *proxy* for actual raise in the faulting coroutine ⇒ **nonlocal resumption becomes local resumption**.



- While source delivers nonlocal exception immediately, propagation only occurs when faulting becomes active.
  ⇒ must suspend back to or call a member that does a resume of the faulting coroutine
- Faulting coroutine performs local **_Resume** implicitly at detection points for nonlocal exceptions, e.g., in **_Enable**, suspend, resume.
- Handler does not return to the proxy raise; control returns to the implicit local raise at exception delivery, e.g., back in **_Enable**, suspend, resume.
- Multiple nonlocal exceptions are queued and delivered in FIFO order depending on the current enabled exceptions.
- **Nonlocal delivery is initially disabled for a coroutine**, so handlers can be set up before any exception can be delivered (also see Section 5.11, p. 76).
- Hence, nonlocal exceptions must be explicitly enabled before delivery can occur with **_Enable**.
- μC++ allows dynamic enabling and disabling of individual exception types versus all exception types.

```
_Enable <E1><E2>. . . {                 _Disable <E1><E2>. . . {
    // exceptions E1, E2 enabled            // exceptions E1, E2 disabled
}                                       }
```

- No exceptions is shorthand for specifying all nonlocal exceptions.
- Nested **_Enable** *or* **_Disable** blocks are additive ⇒ set of enabled or disabled exceptions increases on entry and decreases on exit.

```
_Enable <E> { // E enabled                  _Disable <E> { // E disabled
    _Enable <F> // E & F enabled                _Disable <F> // E & F disabled
        _Enable { // all except. enabled            _Disable { // all except. disabled
        } //  E & F enabled                         } //  E & F disabled
    } //  E enabled                             } //  E disabled
}                                           }
```

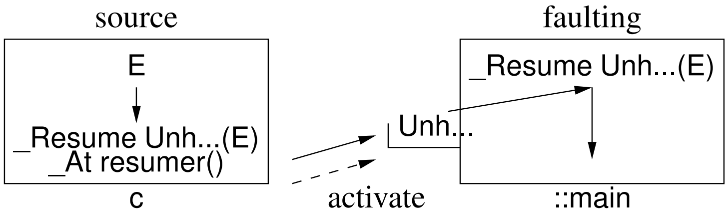
- Nested **_Enable** *and* **_Disable** blocks are subtractive ⇒ set of enabled or disabled exceptions decreases on entry and increases on exit.

```
_Enable <E> { //  E enabled                 _Disable <E> { //  E disabled
    _Disable <E> { //  E disabled               _Enable <E> { //  E enabled
        _Disable { // all except. disabled          _Enable { // all except. enabled
        } //  E disabled                            } //  E enabled
    } //  E enabled                             } //  E disabled
}                                           }
```

- An unhandled exception in a coroutine raises a nonlocal exception of type uBaseCoroutine::UnhandledException at the coroutine's ***last resumer*** and then terminates.

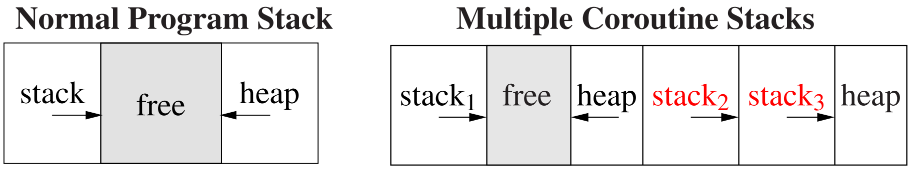
```
_Exception E {};
_Coroutine C {
        void main() { _Throw E(); } // unwind
        // defaultTerminate ⇒ _Resume UnhandledException() _At resumer()
        // ⇒ coroutine activates last resumer (not starter) and terminates
    public:
        void mem() { resume(); } // inside resume is _Resume UnhandledException()
};
int main() {
        C c;
        try { c.mem(); // resume coroutine
        } _CatchResume( uBaseCoroutine::Unh... & ) { ... // option 1: continue after resume
        } catch( uBaseCoroutine::Unh... & ) { ... // option 2: continue after try
        }
}
```

- Call to c.mem resumes coroutine c and then c throws exception E but does not handle it.
- **No _Enable in program main: exception UnhandledException (and a few others) are always enabled.**
- At the base of c's stack, an exception of type uBaseCoroutine::UnhandledException is raised at ::main, since it last resumed c.



- **_CatchResume** continues from resume (dynamic return, fixup)
- **catch** continues after handler (static return, recover)
- Forwarding can occur across any number of coroutines, until a task main forwards and then the program terminates by calling main's set_terminate.
- The original E exception is in UnhandledException and can be thrown by uh.triggerCause().
- *If the original (*E*) exception has a default-terminate routine, it can override* UnhandledException *behaviour (e.g.,* abort*), or return and let it happen.*
- **While the coroutine terminates, control returns to its last resumer rather than its starter.**

3.8 Memory Management



- Normally program stack expands to heap; but coroutine stacks expand to next stack.

- In fact, coroutine stacks are normally allocated in the heap.
- Default µC++ coroutine stack size is 256K **and it does not grow**.
- Adjust initial coroutine stack-size through coroutine constructor:

```
_Coroutine C {
  public:
     C() : uBaseCoroutine( 8192 ) {};      // default 8K stack
     C( int size ) : uBaseCoroutine( size ) {};  // user specified stack size
     . . .
};
C x, y( 16384 );        // x has an 8K stack, y has a 16K stack
```

- Check for stack overflow using coroutine member `verify`:

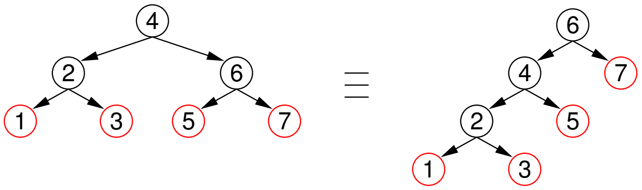
```
void main() {
     . . .           // declarations
     verify();       // check for stack overflow
     . . .           // code
}
```

- Be careful allocating arrays in the coroutine `main`; sometimes necessary to allocate large arrays in heap. (see Point 4, p. 6)

3.9 Semi-Coroutine Examples

3.9.1 Same Fringe

- Two binary trees have same fringe if all leafs are equals from left to right.



- Requires iterator to traverse a tree, return the value of each leaf, and continue the traversal.
- *No direct solution without additional data-structure (e.g., stack) to manage tree traversal.*
- Coroutine uses recursive tree-traversal but suspends during traversal to return value.

```
template< typename T > class Btree {
    struct Node { ... };  ... // other members
  public:
    _Coroutine Iterator {
        Node * cursor;
        void walk( Node * node ) {              // walk tree
          if ( node == nullptr ) return;
            if ( node->left == nullptr && node->right == nullptr ) { // leaf?
                cursor = node;
                suspend();                      // multiple stack frames
            } else {
                walk( node->left );             // recursion
                walk( node->right );            // recursion
            }
        }
        void main() { walk( cursor ); cursor = nullptr; }
      public:
        Iterator( Btree<T> & btree ) : cursor( &btree.root ) {}
        T * next() {
            resume();
            return cursor;
        }
    };
    ... // other members
};
template<class T> bool sameFringe( BTree<T> & tree1, BTree<T> & tree2 ) {
    Btree<T>::Iterator iter1( btree1 ), iter2( btree2 ); // iterator for each tree
    T * t1, * t2;
    for ( ;; ) {
        t1 = iter1.next();  t2 = iter2.next();
      if ( t1 == nullptr || t2 == nullptr ) break; // one traversal complete ?
  if ( *t1 != *t2 ) return false; // elements not equal ?
    }
    return t1 == nullptr && t2 == nullptr; // both traversals completed ?
}
```

3.9.2 Device Driver

- Parse transmission protocol and return message text, e.g.:

…**STX** …message …**ESC ETX** …message …**ETX** 2-byte CRC …

3.9.2.1 Direct

```
int main() {
    enum { STX = '\002', ESC = '\033', ETX = '\003' };
    enum { MaxMsgLnth = 64 };
    unsigned char msg[MaxMsgLnth];
    ...
```

```
    try {
      msg: for ( ;; ) {                       // parse messages
              int lnth = 0, checkval;
              do {
                   byte = input( infile );     // read bytes, throw Eof on eof
              } while ( byte != STX );         // message start ?
           eom: for ( ;; ) {                   // scan message data
                   byte = input( infile );
                   switch ( byte ) {
                     case STX:
                        . . .                  // protocol error
                        continue msg;          // uC++ labelled continue
                     case ETX:                 // end of message
                        break eom;             // uC++ labelled break
                     case ESC:                 // escape next byte
                        byte = input( infile );
                        break;
                   } // switch
                   if ( lnth >= MaxMsgLnth ) { // buffer full ?
                        . . .                  // length error
                        continue msg;          // uC++ labelled continue
                   } // if
                   msg[lnth] = byte;           // store message
                   lnth += 1;
              } // for
              byte = input( infile );          // gather check value
              checkval = byte;
              byte = input( infile );
              checkval = (checkval << 8) | byte;
              if ( ! crc( msg, lnth, checkval ) ) . . . // CRC error
         } // for
    } catch( Eof ) {}
    . . .
} // main
```

3.9.2.2 Coroutine

- Called by interrupt handler for each byte arriving at hardware serial port.

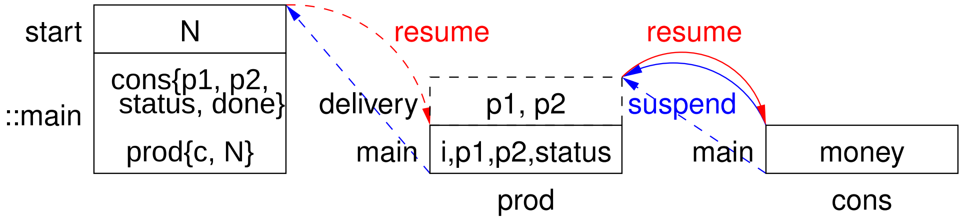
```
_Coroutine DeviceDriver {
    enum { STX = '\002', ESC = '\033', ETX = '\003' };
    enum { MaxMsgLnth = 64 };
    unsigned char byte;
    unsigned char * msg;
  public:
    DeviceDriver( unsigned char * msg ) : msg( msg ) { resume(); }
    void next( unsigned char b ) {          // called by interrupt handler
         byte = b;
         resume();
    }
```

```
  private:
     void main() {
       msg: for ( ;; ) {                      // parse messages
              int lnth = 0, checkval;
              do {
                   suspend();
              } while ( byte != STX );        // message start ?
           eom: for ( ;; ) {                  // scan message data
                   suspend();




                   switch ( byte ) {
                     case STX:
                        . . .                 // protocol error
                        continue msg;         // uC++ labelled continue
                     case ETX:                // end of message
                        break eom;            // uC++ labelled break
                     case ESC:                // escape next byte
                        suspend();            // get escaped character
                        break;
                   } // switch





                   if ( lnth >= MaxMsgLnth ) { // buffer full ?
                        . . .                 // length error
                        continue msg;         // uC++ labelled continue
                   } // if
                   msg[lnth] = byte;          // store message
                   lnth += 1;
              } // for





              suspend();                      // gather check value
              checkval = byte;
              suspend();
              checkval = (checkval << 8) | byte;
              if ( ! crc( msg, lnth, checkval ) ) . . . // CRC error
         } // for
     } // main
}; // DeviceDriver
```

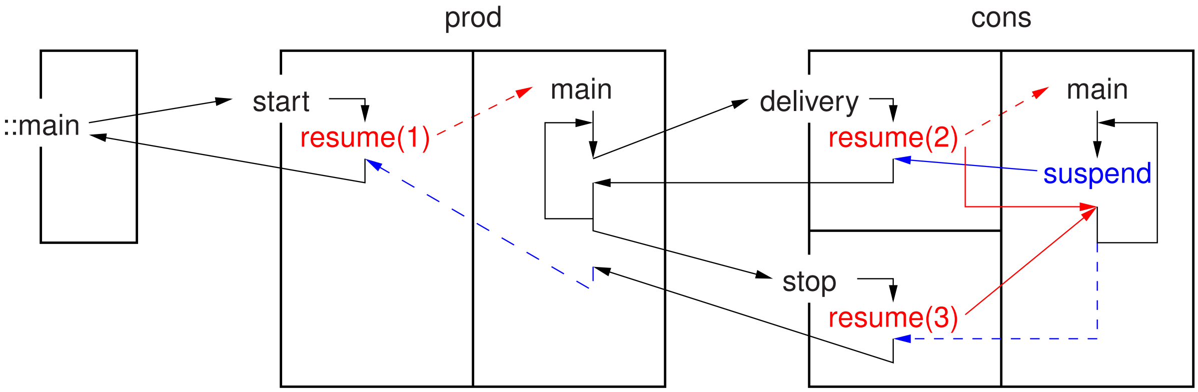
3.9.3 Producer-Consumer

```
_Coroutine Cons {
    int p1, p2, status;  bool done;
    void main() { // starter prod
        // 1st resume starts here
        int money = 1;
        for ( ; ! done; ) {
            cout << "cons " << p1 << " "
                << p2 << " pay $"
                << money << endl;
            status += 1;
            suspend();              // activate delivery or stop
            money += 1;
        }
        cout << "cons stops" << endl;
    } // suspend / resume(starter)
  public:
    Cons() : status(0), done(false) {}
    int delivery( int p1, int p2 ) {
        Cons::p1 = p1; Cons::p2 = p2;
        resume();                   // activate main
        return status;
    }
    void stop() { done = true;  resume(); } // activate main
};

_Coroutine Prod {
    Cons & c;
    int N;
    void main() { // starter ::main
        // 1st resume starts here
        for ( int i = 0; i < N; i += 1 ) {
            int p1 = rand() % 100; // products
            int p2 = rand() % 100;
            cout << "prod " << p1
                << " " << p2 << endl;
            int status = c.delivery( p1, p2 );
            cout << " stat " << status << endl;
        }
        c.stop();
        cout << "prod stops" << endl;
    } // suspend / resume(starter)

  public:
    Prod( Cons & c ) : c(c) {}
    void start( int N ) {
        Prod::N = N;
        resume();                   // activate main
    }
};
```

```
int main() {
      Cons cons;                       // create consumer
      Prod prod( cons );               // create producer
      prod.start( 5 );                 // start producer
}
```



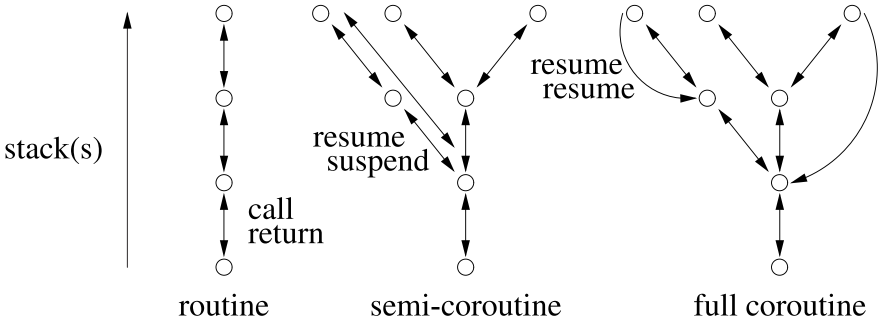
- Do both Prod and Cons need to be coroutines?
- When coroutine main returns, it activates the coroutine that *started* main.
- The **starter** coroutine is the coroutine that does the first resume (cocall).
    - prod started cons.main, so control goes to prod suspended in stop.
    - ::main started prod.main, so control goes to ::main suspended in start.
- For semi-coroutines, the starter is often the last (only) resumer, so it seems coroutine main implicitly suspends on termination.



- **dashed red** ⇒ create stack and resume coroutine main (cocall)
- **solid red** ⇒ resume coroutine at last suspend
- **solid blue** ⇒ resume last resumer
- **dashed blue** ⇒ resume *starter*

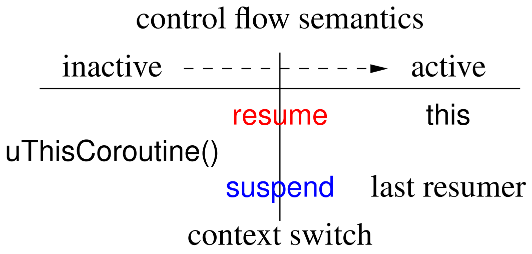
3.10 Full Coroutines

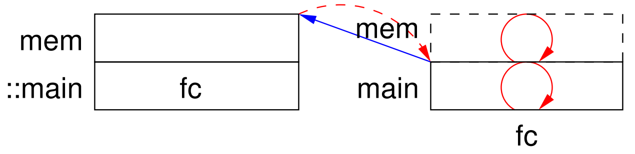
- **Semi-coroutine** activates the member routine that activated it.
- **Full coroutine** has a resume cycle; semi-coroutine does not form a resume cycle.

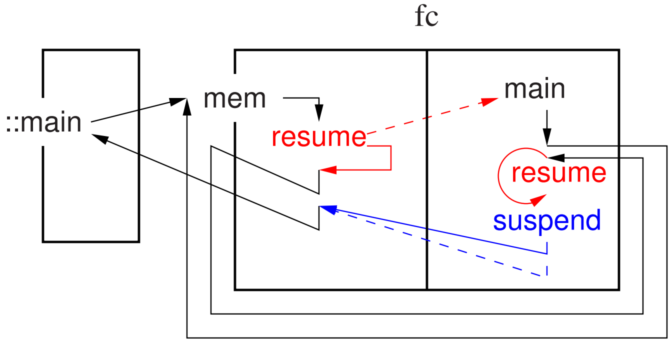


- A semi-coroutine is allowed to perform call/return operations because it subsumes the notion of a routine.
- A full coroutine is allowed to perform semi-coroutine operations because it subsumes the notion of semi-coroutine.

```
_Coroutine Fc {
    void main() { // starter ::main
        mem();       // ?
        resume();    // ?
        suspend();   // ?
    }                // ?
  public:
    void mem() { resume(); }
};
int main() {
    Fc fc;
    fc.mem();
}
```







- Suspend inactivates the current active coroutine (uThisCoroutine), and activates last resumer.
- Resume inactivates the current active coroutine (uThisCoroutine), and activates the current object (**this**).
- Hence, the current object *must* be a non-terminated coroutine.

- Note, **this** and `uThisCoroutine` change at different times.
- Exception: last resumer not changed when resuming self because no practical value.
- Full coroutines can form an arbitrary topology with an arbitrary number of coroutines.
- There are 3 phases to any full coroutine program.
  1. starting the cycle
  2. executing the cycle
  3. stopping the cycle (return to the program `main`)
- Starting the cycle requires each coroutine to know at least one other coroutine.
- The problem is mutually recursive references.

```
Fc x(y), y(x);  // does not compile, why?
```

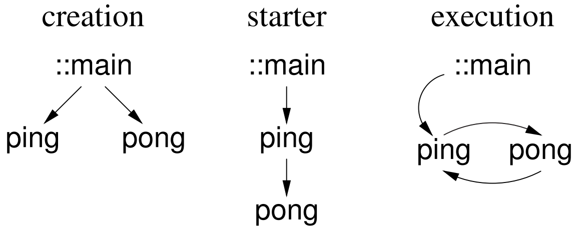
- One solution is to make closing the cycle a special case.

```
Fc x, y(x);
x.partner( y );
```

- Once the cycle is created, execution around the cycle can begin.
- Stopping can be as complex as starting, ***because a coroutine goes back to its starter***.
- For full-coroutines, the starter is often *not* the last resumer, so coroutine `main` does not appear to implicitly `suspend` on termination.
- But it is necessary to activate the program `main` to finish (unless `exit` is used).
- The starter stack always gets back to the program `main`.
- Again, it is unnecessary to terminate all coroutines, just delete them.

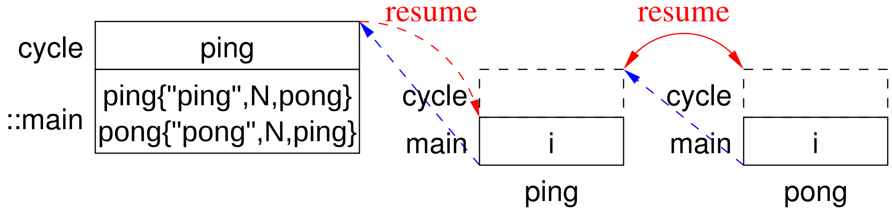
3.10.1 Ping/Pong

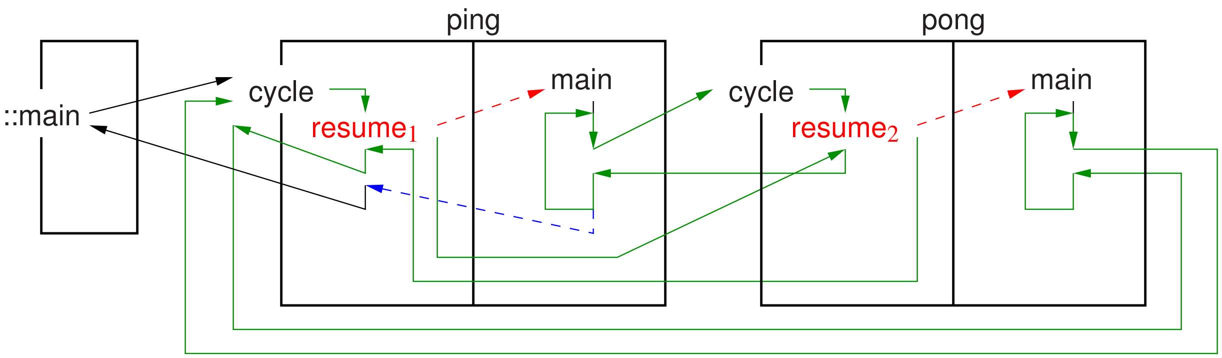
- Full-coroutine control-flow with 2 identical coroutines:



```
_Coroutine PingPong {
    const char * name;
    const unsigned int N;
    PingPong * part;
    void main() {  // ping's starter ::main, pong's starter ping
        for ( unsigned int i = 0; i < N; i += 1 ) {
            cout << name << endl;
            part->cycle();
        }
    }
  public:
    PingPong( const char * name, unsigned int N, PingPong & part )
        : name( name ), N( N ), part( &part ) {}
    PingPong( const char * name, unsigned int N ) : name( name ), N( N ) {}
    void partner( PingPong & part ) { PingPong::part = &part; }
    void cycle() { resume(); }
};
int main() {
    enum { N = 20 };
    PingPong ping( "ping", N ), pong( "pong", N, ping );
    ping.partner( pong );
    ping.cycle();
}
```

- ping created without partner; pong created with partner.
- ping makes pong partner, closing cycle.
- Why is PingPong::part a pointer rather than reference?
- cycle resumes ping ⇒ ::main is ping's starter
- ping calls pong's cycle member, resuming pong so ping is pong's starter.
- pong calls ping's cycle member, **resuming ping in pong's cycle member**.
- Each coroutine cycles N times, **becoming inactive in the other's cycle member**.
  - ping ends first, because it started first, resuming its starter ::main in ping's cycle member.
  - ::main terminates with terminated coroutine ping and unterminated coroutine pong.
- Assume ping's declaration is changed to ping("ping", N + 1).
  - pong ends first, because it cycles less, resuming its starter ping in pong's cycle member.
  - ping ends second, resuming its starter ::main in ping's cycle member.
  - ::main terminates with terminated coroutines ping and pong.





3.10.2 Producer-Consumer

- Full-coroutine control-flow and bidirectional communication with 2 non-identical coroutines:

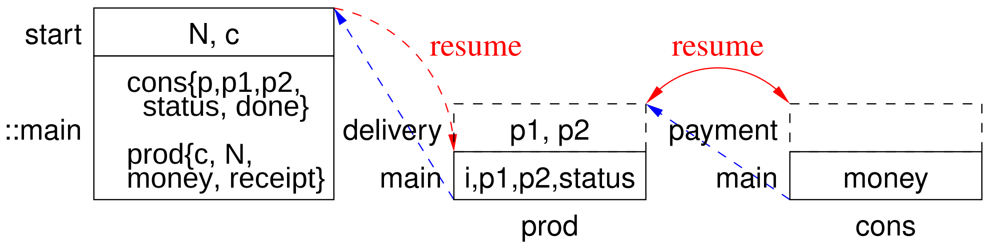
```
_Coroutine Prod {
    Cons * c;
    int N, money, receipt;
    void main() { // starter ::main
        // 1st resume starts here
        for ( int i = 0; i < N; i += 1 ) {
            int p1 = rand() % 100; // products
            int p2 = rand() % 100;
            cout << "prod " << p1
                << " " << p2 << endl;
            int status = c->delivery(p1, p2);
            cout << "prod rec $" << money
              << " stat " << status << endl;
            receipt += 1;
        }
        c->stop();
        cout << "prod stops" << endl;
    }
```

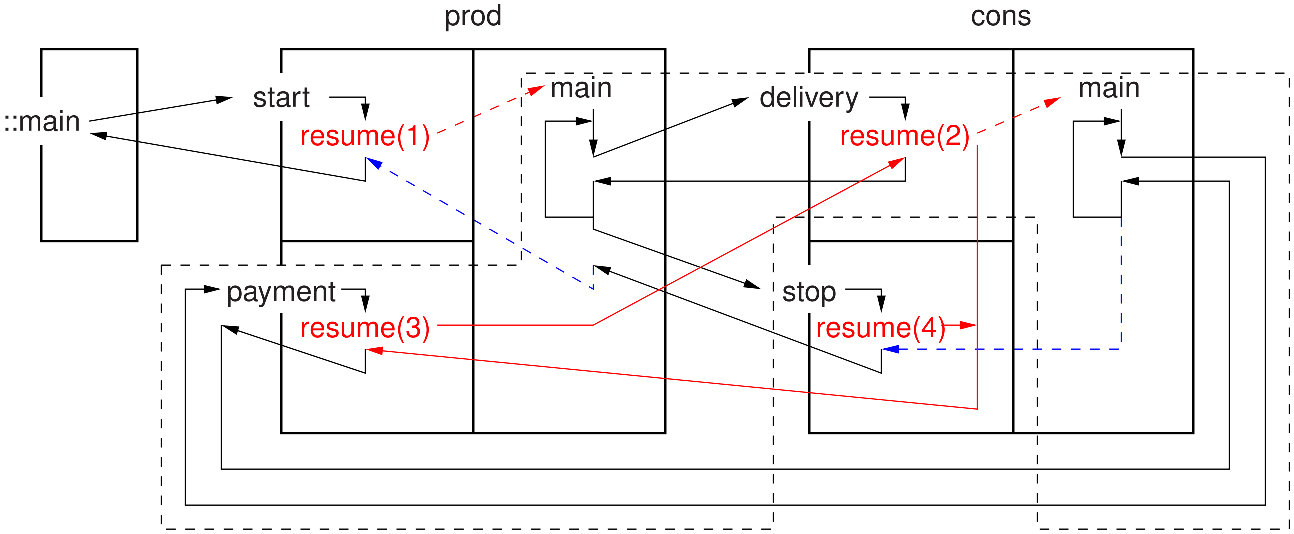
```
  public:
    int payment( int money ) {
        Prod::money = money;
        resume();        // activate prod in
        return receipt; // Cons::delivery
    }
    void start( int N, Cons & c ) {
        Prod::N = N; Prod::c = &c;
        receipt = 0;
        resume(); // activate Prod::main
    }
};
```

```
_Coroutine Cons {
    Prod & p;
    int p1, p2, status;
    bool done;
    void main() { // starter prod
        // 1st resume starts here
        int money = 1, receipt;
        for ( ; ! done; ) {
            cout << "cons " << p1 << " "
                << p2 << " pay $"
                << money << endl;
            status += 1;
            receipt = p.payment(money);
            cout << "cons #"
                << receipt << endl;
            money += 1;
        }
        cout << "cons stops" << endl;
    }
```

```
  public:
    Cons(Prod & p) : p(p), status(0), done(false) {}
    int delivery( int p1, int p2 ) {
        Cons::p1 = p1; Cons::p2 = p2;
        resume(); // Cons::main 1st time, then
        return status; // cons in Prod::payment
    }
    void stop() {
        done = true;
        resume(); // cons in Prod::payment
    }
};
int main() {
    Prod prod;
    Cons cons( prod );
    prod.start( 5, cons );
}
```

- Cheat using forward reference for `Cons` at `c->delivery` and `c->stop`. Fix by?





- Black dashed-line same control flow as ping/pong.

- Remove flag variable from full-coroutine producer-consumer.

```
_Exception Stop {};
_Coroutine Prod {
    Cons * c;
    int N, money, receipt;
    void main() {
        for ( int i = 0; i < N; i += 1 ) {
            int p1 = rand() % 100;
            int p2 = rand() % 100;
            cout << "prod " << ...
            int status = c->delivery(p1, p2);
            cout << "prod rec $" << ...
            receipt += 1;
        }
        _Resume Stop() _At *c;
        suspend(); // restart cons
        cout << "prod stops" << endl;
    }
  public:
    int payment( int money ) {
        Prod::money = money;
        resume();
        return receipt;
    }
    void start( int N, Cons & c ) {
        Prod::N = N; Prod::c = &c;
        receipt = 0;
        resume();
    }
};
```

```
_Coroutine Cons {
    Prod & p;
    int p1, p2, status = 0;
    void main() {
        int money = 1, receipt;
        try {
            for ( ;; ) {
                cout << "cons " << p1 << ...
                status += 1;
                receipt = p.payment( money );
                cout << "cons #" << ...
                _Enable; // trigger exception
                money += 1;
            }
        } catch( Stop & ) {}
        cout << "cons stops" << endl;
    }
  public:
    Cons( Prod & p ) : p( p ) {}
    int delivery( int p1, int p2 ) {
        Cons::p1 = p1; Cons::p2 = p2;
        resume();
        return status;
    }
};
```

3.11 Coroutine Languages

- Coroutine implementations have two forms:

    1. stackless: use the caller’s stack and a fixed-sized local-state

    2. stackful: separate stack and a fixed-sized (class) local-state

- Stackless coroutines cannot call other routines and then suspend, i.e., only suspend in the coroutine main.

- Generators/iterators are often simple enough to be stackless using yield.

- Simula, CLU, C#, Ruby, Python, JavaScript, Lua, F# all support yield constructs.

3.11.1 Python 3.5

- Stackless, semi coroutines, routine versus class, no calls, single interface

- Fibonacci (see Section 3.1.1.4, p. 26)

```
def Fibonacci( n ):                     # coroutine main
    fn = 0;  fn1 = fn
    yield fn                            # suspend
    fn = 1; fn2 = fn1; fn1 = fn
    yield fn                            # suspend
    # while True:                       # for infinite generator
    for i in range( n - 2 ):
        fn = fn1 + fn2; fn2 = fn1; fn1 = fn
        yield fn                        # suspend

f1 = Fibonacci( 10 )                    # objects
f2 = Fibonacci( 10 )
for i in range( 10 ):
    print( next( f1 ), next( f2 ) )     # resume
for fib in Fibonacci( 15 ):             # use generator as iterator
    print( fib )
```

- Format (see Section 3.1.2.4, p. 30)

```
def Format():
    try:
        while True:
            for g in range( 5 ):        # groups of 5 blocks
                for b in range( 4 ):    # blocks of 4 characters
                    print( (yield), end='' ) # receive from send
                print( '  ', end='' )   # block separator
            print()                     # group separator
    except GeneratorExit:               # destructor
        if g != 0 | b != 0:             # special case
            print()

fmt = Format()
next( fmt )                             # prime generator
for i in range( 41 ):
    fmt.send( 'a' )                     # send to yield
```

- send takes only one argument, and no cycles ⇒ no full coroutine

3.11.2 JavaScript

- Similar to Python: stackless, semi coroutines, routine versus class, no calls, single interface
- Embedded in HTML with I/O from web browser.
- Fibonacci (see Section 3.1.1.4, p. 26)

```
<!DOCTYPE html><html>
<head><meta charset="utf-8" /><title>Fibonacci Coroutine</title></head>
<body><button id="button">Click for next Fibonacci number!</button>
    <p id="output"></p></body>
<script>
```

```
function * Fibonacci() {
     var fn = 0, fn1 = 0, fn2 = 0;          // JS bug: initialize vars or lost on suspend
     yield fn;                              // return fn to resumer
     fn = 1; fn2 = fn1; fn1 = fn;
     yield fn;                              // return fn to resumer
     for ( ;; ) {
          fn = fn1 + fn2; fn2 = fn1; fn1 = fn;
          yield fn;                         // return fn to resumer
     }
}
const button = document.getElementById( ′button′ );
const output = document.getElementById( ′output′ );
var count = 0, suffix;
var fib = Fibonacci();
button.addEventListener( "click", event => {
     if (count % 10 == 1) suffix = "st";
     else if (count % 10 == 2) suffix = "nd";
     else suffix = "th";
     output.textContent = count + suffix + " Fibonacci: " + fib.next().value;
     count += 1;
});
</script></body></html>
```

- Format (see Section 3.1.2.4, p. 30)

```
<!DOCTYPE html><html>
<head><meta charset="utf-8" /><title>Format Coroutine</title></head>
<body><input placeholder="Type characters!" size=50><p id="output"></p></body>
<script>
function * Format() {
     var g = 0, b = 0, ch = ′′;        // JS bug: initialize vars or lost on suspend
     for ( ;; ) {
          for ( g = 0; g < 5; g += 1 ) {
               for (b = 0; b < 4; b += 1) {
                    ch = yield;
                    output.innerHTML += ch; // console.log adds \n
               }
               output.innerHTML  += "  ";
          }
          output.innerHTML += "<br>";
     }
}
const inputBox = document.querySelector( ′input′ );
const output = document.getElementById( ′output′ );
var format = Format();
format.next();                         // prime generator
inputBox.addEventListener( ′keypress′, event => {
     format.next( event.key );
});
</script></body></html>
```

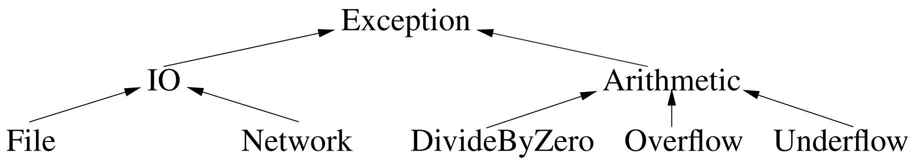
3.11.3 C++20 Coroutines

- C++20 has an API for coroutines and outline code to build stackless, stackful, or even fibres (tasks without preemption).
- This capability cannot be used directly. It requires writing significant low-level implementation code.

4 More Exceptions

4.1 Derived Exception-Type

- **derived exception-types** is a mechanism for inheritance of exception types, like class inheritance.
- Provides a kind of polymorphism among exception types:



- Provides ability to handle an exception at different degrees of specificity along the hierarchy.
- Possible to catch a more general exception-type in higher-level code where the implementation details are unknown.
- Higher-level code should catch general exception-types to reduce tight coupling to the specific implementation.
  - tight coupling forces unnecessary changes in the higher-level code when low-level code changes.
- Exception-type inheritance allows a handler to match multiple exceptions, e.g., a base handler can catch both base and derived exception-type.
- To handle this case, most propagation mechanisms perform a linear search of the handlers for a guarded block and select the first matching handler.

```
try { . . .
} catch( Arithmetic & ) { . . .
} catch( Overflow ) { . . . // never selected!!!
}
```

- When subclassing, it is best to catch an exception by reference:

```
struct B {};
struct D : public B {};
try {                                  try {
    throw D(); // _Throw in uC++           throw D(); // _Throw in uC++
} catch( B e ) { // truncation         } catch( B & e ) { // no truncation
    // cannot down-cast                    . . . dynamic_cast<D>(e) . . .
}                                      }
```

  - Otherwise, exception is truncated from its dynamic type to static type specified at the handler, and cannot be down-cast to the dynamic type.
- Notice, catching truncation (see page 55) is different from raising truncation, which does not occur in μC++ with **_Throw**.

4.2 Catch-Any

- **catch-any** is a mechanism to match any exception propagating through a guarded block.

- With exception-type inheritance, catch-any can be provided by the root exception-type, e.g., **catch**(Exception) in Java.
- Otherwise, special syntax is needed, e.g., **catch**(...) in C++.
- For termination, catch-any is used as a general cleanup when a non-specific exception occurs.
- For resumption, this capability allows a guarded block to gather or generate information about control flow (e.g., logging).

```
try {
    . . .
} _CatchResume( . . . ) { // catch-any
    . . .           // logging
    _Resume;        // reresume for fixup
} catch( . . . ) {  // catch-any
    . . .           // cleanup
    _Throw;         // rethrow for recovery
}
```

- Java finalization:

```
try { . . .
} catch( E ) { . . . }
. . . // other catch clauses
} finally { // always executed
    . . . // cleanup
    // possibly rethrow
}
```

  provides catch-any capabilities and handles the non-exceptional case.

  - difficult to mimic in C++, even with RAII, because of local variables.

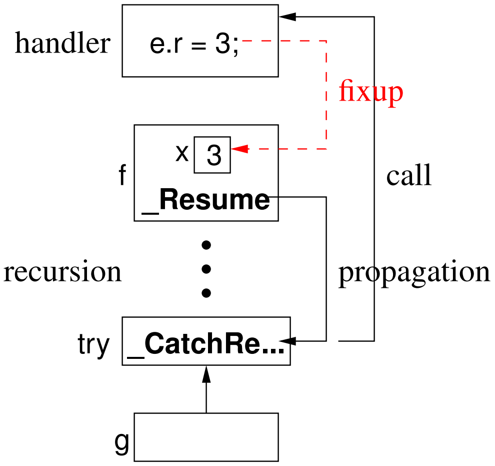
4.3 Exception Parameters

- **Exception parameters** allow passing information from the raise to a handler.
- Inform a handler about details of the exception, and to modify the raise site to fix an exceptional situation.
- Different EHMs provide different ways to pass parameters.
- In C++/Java, parameters are defined inside the exception:

```
struct E {
    int i;
    E( int i ) : i(i) {}
};
void f( . . . ) { . . . throw E( 3 ); . . . } // argument
int main() {
    try {
        f( . . . );
    } catch( E p ) { // parameter, value or reference
        . . . p.i . . .
    }
}
```

- For resumption, values at raise modified via reference/pointer in caught exception:

```
_Exception E {
  public:
     int & r;
     E( int & r ) : r( r ) {}
};
void f() {
     int x;
     . . . _Resume E( x ); . . .
}
void g() {
     try {
          f();
     } _CatchResume( E & e ) {
          . . . e.r = 3; . . .
     }
}
```



4.4 Exception List

- Missing exception handler for arithmetic overflow in control software caused Ariane 5 rocket to self-destruct ($370 million loss).
- **exception list** is part of a routine's prototype specifying which exception types may propagate from the routine to its caller.

```
int g() throw(E) { . . . throw E(); }
```

- This capability allows:
  - static detection of a raised exception not handled locally or by its caller
  - runtime detection where the exception may be converted into a special **failure exception** or the program terminated.
- 2 kinds of checking:
  - checked/unchecked exception-type (Java, inheritance based, static check)
  - checked/unchecked routines (C++, exception-list based, dynamic check) (deprecated C++11, replaced with **noexcept**)
- While checked exception-types are useful for software engineering, reuse is precluded.
- E.g., consider the simplified C++ template routine sort:

```
template<class T> void sort( T items[] ) throw( ?, ?, ... ) {
     // using bool operator<( const T &a, const T &b );
```

  using the operator routine < in its definition.
- Impossible to know all exception types that propagated from routine < for every type.
- Since only a fixed set of exception types can appear in sort's exception list, some sortable types are precluded.
- Exception lists can preclude reuse for arguments of routine pointers (functional style) and/or polymorphic methods/routines (OO style):

```
struct E {};

// throw NO exceptions
void f( void (*p)() noexcept ) {
    p();
}
void g() noexcept(false) { throw E(); }
void h() {
    try { . . . f( g ); . . .
    } catch( E ) {}
}
```

```
struct B { // throw NO exceptions
    virtual void g() noexcept {}
    void f() { g(); }
};
struct D : public B {
    void g() noexcept(false) { throw E(); }
    void h() {
        try { . . . f(); . . .
        } catch( E ) {}
    }
};
```

- Left, routine h has an appropriate **try** block and passes the version of g to f raising exception E.
- However, checked exception-types preclude this case because the signature of argument g is less restrictive than parameter p of f.
- Right, member routine D::h calls B::f, which calls D::g that raises exception E.
- However, checked exception types preclude this case because the signature of D::g is less restrictive than B::g.
- Finally, determining an exception list for a routine can become impossible for concurrent exceptions because they can propagate at any time.

4.5 Destructor

- Destructor is implicitly **noexcept** ⇒ ***cannot*** raise an exception.
- Destructor ***can*** raise an exception, if marked **noexcept**(**false**), or inherits from class with **noexcept**(**false**) destructor.

```
struct E {};
struct C {
    ~C() noexcept(false) { throw E(); }
};
try {           // outer try
    C x;        // raise on deallocation
    try {       // inner try
        C y; // raise on deallocation
    } catch( E ) {. . .}  // inner handler
} catch( E ) {. . .}  // outer handler
```

```
y's destructor         x's destructor
    | throw E              | throw E
inner try              outer try
    | y                    | x
```

  - y's destructor called at end of inner **try** block, it raises an exception E, which unwinds destructor and **try**, and handled at inner **catch**
  - x's destructor called at end of outer **try** block, it raises an exception E, which unwinds destructor and **try**, and handled at outer **catch**

4.6 Multiple Exceptions

- An exception handler can generated an arbitrary number of nested exceptions.

```
struct E {};
int cnt = 3;
void f( int i ) {
    if ( i == 0 ) throw E();
    try {
        f( i - 1 );
    } catch( E ) { // handler h
        cnt -= 1;
        if ( cnt > 0 ) f( 2 );
        . . . throw; . . .
    }
}
int main() { f( 2 ); }
```

h ~~f~~
f
f
h ~~f~~ throw E_2
f
f
h ~~f~~ throw E_1
f
f

- Exceptions are nested as handler can rethrow its matched exception when control returned.
- However, multiple exceptions cannot propagate simultaneously.
  - Cannot start second exception without handler to deal with first exception, i.e., cannot drop exception and start another.
  - Cannot postpone first exception because second exception may remove its handlers during stack unwinding.
- Only destructor code can intervene during propagation.
- Hence, a destructor ***cannot*** raise an exception during propagation; it can only start propagation.

```
try {
    C x;            // raise on deallocation
    throw E();
} catch( E ) {. . .}
```

- Raise of E causes unwind of inner **try** block.
- x's destructor called during unwind, it raises an exception E, which one should be used?
- Check if exception is being propagated with `uncaught_exceptions()`.

5 Concurrency

- A **thread** is an independent sequential execution path through a program.
  - Each thread is scheduled for execution separately and independently from other threads.
- A **process** is a program component (like a routine) that **has its own thread** and has the same state information as a coroutine.
- A **task** is a program component that **has its own thread** but is
  - reduced along some particular dimension (like the difference between a boat and a ship, one is physically smaller than the other).
  - It is often the case that a process has its own memory, while tasks share a common memory.
  - A task is sometimes called a light-weight process (LWP).
- **Parallel execution** is when 2 or more operations occur simultaneously, which can only occur when multiple processors (CPUs) are present.
- **Concurrent execution** is any situation in which execution of multiple threads *appears* to be performed in parallel.
  - It is the threads of control associated with processes and tasks that result in concurrent execution, **not the processors**.

5.1 Why Write Concurrent Programs

- Dividing a problem into multiple executing threads is an important programming technique just like dividing a problem into multiple routines.
- Expressing a problem with multiple executing threads may be the natural (best) way of describing it.
- Multiple executing threads can enhance execution-time efficiency by taking advantage of inherent concurrency in an algorithm and any parallelism available in the computer system.

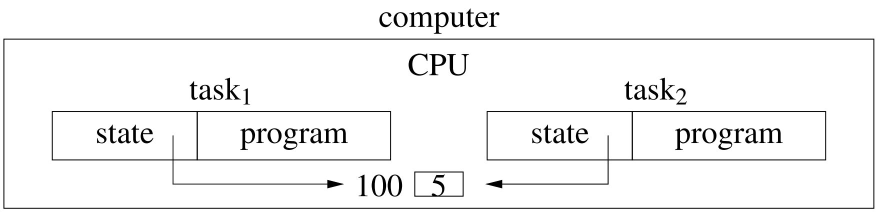
5.2 Why Concurrency is Difficult

- to understand:
  - While people can do several things concurrently, the number is small because of the difficulty in managing and coordinating them.
  - Especially when the things interact with one another.
- to specify:
  - How can/should a problem be broken up so that parts of it can be solved at the same time as other parts?
  - How and when do these parts interact or are they independent?
  - If interaction is necessary, what information must be communicated during the interaction?
- to debug:
  - Concurrent operations proceed at varying speeds and in non-deterministic order, hence execution is not repeatable (Heisenbug).

  - ○ Reasoning about multiple streams or threads of execution and their interactions is much more complex than for a single thread.
- E.g. Moving furniture out of a room; can't do it alone, but how many helpers and how to do it quickly to minimize the cost?
- How many helpers?
  - ○ 1,2,3, ... N, where N is the number of items of furniture
  - ○ more than N?
- Where are the bottlenecks?
  - ○ the door out of the room, items in front of other items, large items
- What communication is necessary between the helpers?
  - ○ which item to take next
  - ○ some are fragile and need special care
  - ○ big items need several helpers working together

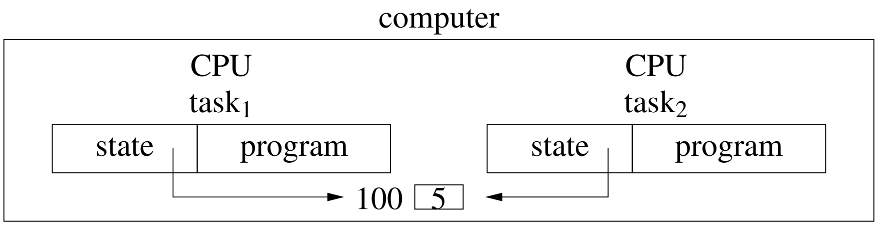
5.3 Concurrent Hardware

- Concurrent execution of threads is possible with only one CPU (**uniprocessor**); **multitasking** for multiple tasks or **multiprocessing** for multiple processes.

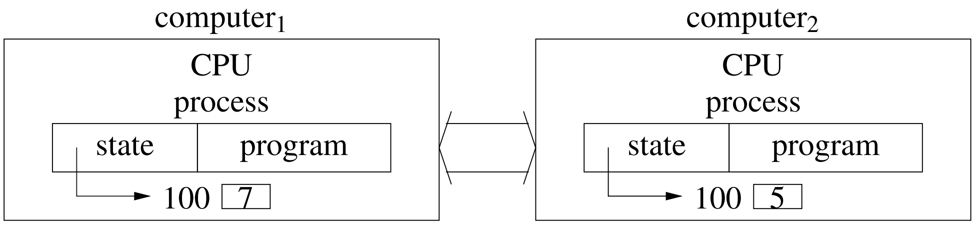


  - ○ Parallelism is simulated by context switching the threads on the CPU.
  - ○ Most of the issues in concurrency can be illustrated without parallelism.
  - ○ Pointers among tasks work because memory is shared.
  - ○ **Unlike coroutines, task switching may occur at non-deterministic program locations, i.e., between any two *machine* instructions.**
  - ○ Introduces all the difficulties in concurrent programs.
    - ∗ programs must be written to work regardless of non-deterministic ordering of program execution.
  - ○ Switching happens *explicitly* but conditionally when calling routines.
    - ∗ routine may or may not context switch depending on hidden (internal) state (cannot predict)
  - ○ Switching can happen *implicitly* because of an external **interrupt** independent of program execution.
    - ∗ e.g., page fault, I/O, or timer interrupt
    - ∗ timer interrupts divide execution (between instructions) into discrete time-slices occurring at non-deterministic time intervals
    - ∗ ⇒ **task execution is not continuous**

  - If interrupts affect **scheduling** (execution order), it is called **preemptive**, otherwise the scheduling is **non-preemptive**.
  - Programmer cannot predict execution order, unlike coroutines.
  - Granularity of context-switch is instruction level for preemptive (harder to reason) and routine level for non-preemptive.
- In fact, every computer has multiple CPUs: main CPU(s), bus CPU, graphics CPU, disk CPU, network CPU, etc.
- Concurrent/parallel execution of threads is possible with multiple CPUs sharing memory (**multiprocessor**):



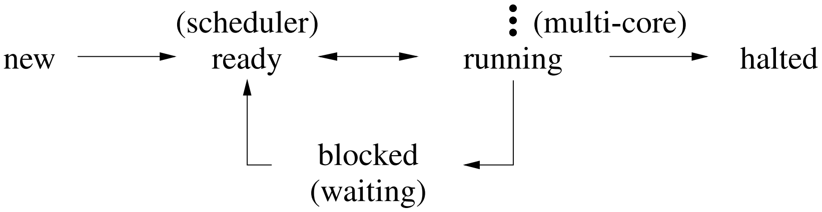
- Pointers among tasks work because memory is shared.
- Concurrent/parallel execution of threads is possible with single/multiple CPUs on different computers with *separate memories* (**distributed system**):



- Pointers among tasks do NOT work because memory is not shared.

5.4 Execution States

- A thread may go through the following states during its execution.



- **State transitions** are initiated in response to events (e.g., interrupts):
  - entering the system (new → ready)
  - assigning thread to computing resource, e.g., CPU (ready → running)
  - timer alarm for preemption (running → ready)

  - long-term delay versus spinning (running → blocked)
  - completion of delay, e.g., network or I/O completion (blocked → ready)
  - normal completion or error, e.g., segment fault (running → halted)

- Thread cannot bypass the "ready" state during a transition so the scheduler maintains complete control of the system.
- Non-deterministic "ready ↔ running" transition ⇒ basic operations unsafe:

```
int i = 0;    // shared
task0         task1
i += 1        i += 1
```

- If increment implemented with single `inc i` instruction, transitions can only occur before or after instruction, not during.
- If increment is replaced by a load-store sequence, transitions can occur during sequence.

```
ld   r1,i     // load into register 1 the value of i
...           // PREEMPTION
add r1,#1     // add 1 to register 1
...           // PREEMPTION
st   r1,i     // store register 1 into i
```

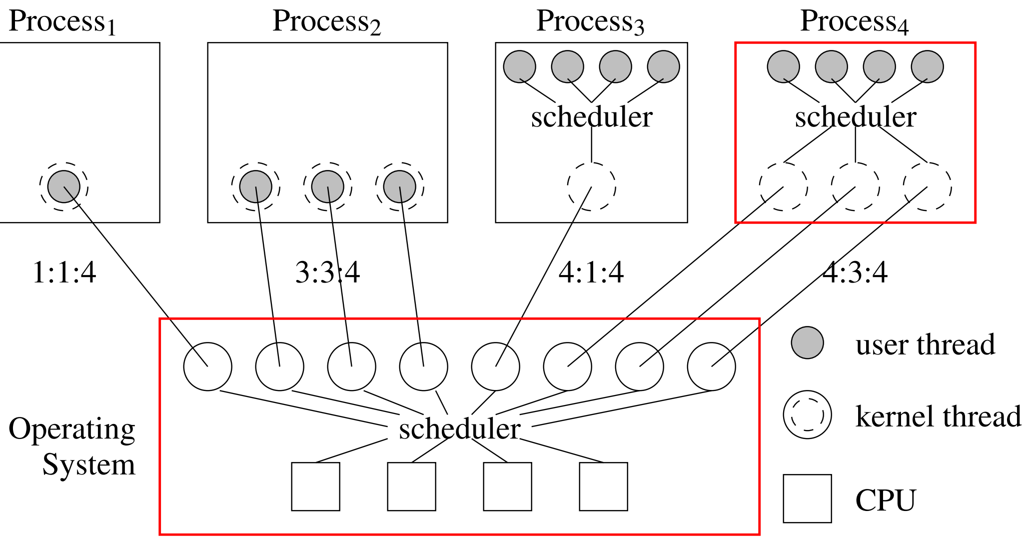
- If both tasks increment 10 times, the expected result is 20.
- True for single instruction, false for load-store sequence.
- Many failure cases for load-store sequence where i does not reach 20.
- Remember, context switch saves and restores registers for each coroutine/task.

```
        task0                       task1

1st iteration
ld   r1,i     (r1 <- 0)
add r1,#1     (r1 <- 1)
                            1st iteration
                            ld   r1,i     (r1 <- 0)
                            add r1,#1     (r1 <- 1)
                            st   r1,i     (i   <- 1)
                            2nd iteration
                            ld   r1,i     (r1 <- 1)
                            add r1,#1     (r1 <- 2)
                            st   r1,i     (i   <- 2)
                            3rd iteration
                            ld   r1,i     (r1 <- 2)
                            add r1,#1     (r1 <- 3)
                            st   r1,i     (i   <- 3)
1st iteration
st   r1,i     (i  <- 1)
```

- The 3 iterations of **task1** are lost when overwritten by **task0**.
- Hence, sequential operations, however small (increment), are unsafe in a concurrent program.

5.5 Threading Model

- For multiprocessor systems, a **threading model** defines relationship between threads and CPUs.
- OS manages CPUs providing logical access via **kernel threads** (**virtual processors**) *scheduled* across the CPUs.



- More kernel threads than CPUs to provide multiprocessing, i.e., run multiple programs simultaneously.
- A process may have multiple kernel threads to provide parallelism if multiple CPUs.
- A program may have user threads scheduled on its process's kernel threads.
- User threads are a low-cost structuring mechanism, like routines, objects, coroutines (versus high-cost kernel thread).
- Relationship is denoted by user:kernel:CPU, where:
  - 1:1:C (kernel threading) – 1 user thread maps to 1 kernel thread
  - N:N:C (generalize kernel threading) – N × 1:1 kernel threads (Java/Pthreads/C++)
  - M:1:C (user threading) – M user threads map to 1 kernel thread (no parallelism)
  - M:N:C (user threading) – M user threads map to N kernel threads (Go, μC++)
- Often the CPU number (C) is omitted.
- Can recursively add **nano threads** (stackless) on top of user threads (stackful), and **virtual machine** below OS.

5.6 Concurrent Systems

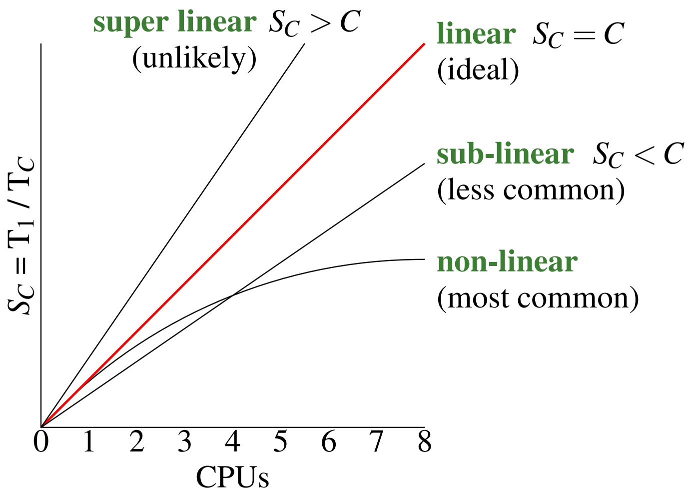
- Concurrent systems can be divided into 3 major types:
  1. those that attempt to **discover** ***implicit*** concurrency in an otherwise sequential program, e.g., parallelizing loops and access to data structures
  2. those that provide concurrency through ***implicit*** constructs, which a programmer uses to build a concurrent program

3. those that provide concurrency through ***explicit*** constructs, which a programmer uses to build a concurrent program

- In type 1, there is a fundamental limit to how much concurrency can be found and current techniques only work on a certain class of problems.
- In type 2, concurrency is accessed indirectly via specialized mechanisms (e.g., pragmas or parallel **for**) and threads are implicitly managed.
- In type 3, concurrency is accessed directly and threads explicitly managed.
- Types 1 & 2 are always built from type 3.
- **To solve all concurrency problems, threads need to be explicit.**
- Both implicit and explicit mechanisms are complementary, and hence, can appear together in a single programming language.
- However, the limitations of implicit mechanisms require that explicit mechanisms always be available to achieve maximum concurrency.
- Some concurrent systems provide a single technique or paradigm that must be used to solve all concurrent problems.
- While a particular paradigm may be very good for solving certain kinds of problems, it may be awkward or preclude other kinds of solutions.
- Therefore, a good concurrent system must support a variety of different concurrent approaches, while at the same time not requiring the programmer to work at too low a level.
- In all cases, as concurrency increases, so does the complexity to express and manage it.

5.7 Speedup

- Program **speedup** is $S_C = T_1 / T_C$, where C is number of CPUs and T_1 is sequential execution.
- E.g., 1 CPU takes 10 seconds, $T_1 = 10$ (**user time**), 4 CPUs takes 2.5 seconds, $T_4 = 2.5$ (**real time**) $\Rightarrow S_4 = 10/2.5 = 4$ times speedup (linear).



- Aspects affecting speedup (assume sufficient parallelism for concurrency):

1. amount of concurrency
2. critical path among concurrency
3. scheduler efficiency

- An algorithm/program is composed of sequential and concurrent sections.
- E.g., sequentially read matrix, concurrently subtotal rows, sequentially total subtotals.
- **Amdahl's law** (Gene Amdahl): concurrent section is $P \Rightarrow$ sequential section $1-P$, maximum speedup using C CPUs is:

$$S_C = \frac{1}{(1-P)+P/C} \quad where\ T_1 = 1, T_C = sequential + concurrent$$

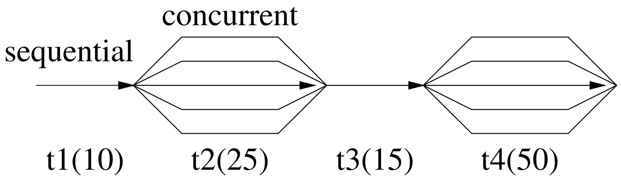
- Normalize: $T_1 = 10/10 = 1$, $T_4 = 2.5/10 = .25$.

$$S_4 = \frac{1}{(1-1)+1\times.25} = 4\ \ times,\ P = 1 \Rightarrow (100\%)\ of\ T_4\ is\ concurrent$$

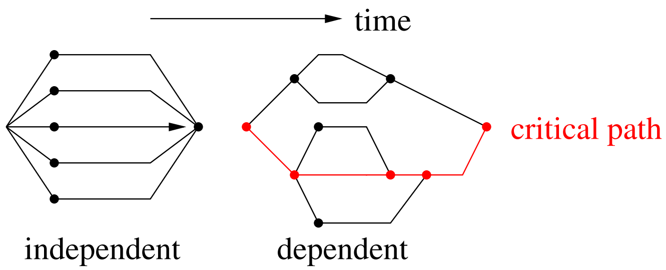
- Change $P = .8(80\%)$ so $T_4 = .8 \times .25 = .2$ is concurrent and $1-.8 = .2(20\%)$ is sequential.

$$S_4 = \frac{1}{(1-.8)+.8\times.25} = \frac{1}{.2+.2} = 2.5\ \ times,\ because\ of\ sequential\ code$$

- As C goes to infinity, P/C goes to 0, so maximum speedup is $1/(1-P)$, i.e., sequential time.
- Speedup falls rapidly as sequential section $(1-P)$ increases.
- E.g., sequential section = $.2(20\%)$, $S_C = 1/(1-.8) \Rightarrow$ max speedup 5.
- **Concurrent programming consists of minimizing sequential section $(1-P)$.**
- E.g., program has 4 stages: $t1$ = 10, $t2$ = 25, $t3$ = 15, $t4$ = 50 (time units)



- Concurrent stages performs **scatter/gather pattern**; scatter data/computation, gather results.
- T_C = 10 + 25 + 15 + 50 = 100 (time units)
- Concurrently speedup sections $t2$ by 5 times and $t4$ by 10 times.
- T_C = 10 + 25 / 5 + 15 + 50 / 10 = 35 (time units)
  Speedup = 100 / 35 = 2.86 times
- Large reductions for $t2$ and $t4$ have only minor effect on speedup.
- Formula does not consider any increasing costs for the concurrency, i.e., administrative costs, so results are optimistic.
- While sequential sections bound speedup, concurrent sections bound speedup by the **critical path** of computation.



- ◦ **independent execution** : all threads created together and do not interact.
- ◦ **dependent execution** : threads created at different times and interact.

- Longest path bounds speedup (even for independent execution).
- Finally, speedup can be affected by scheduler efficiency/ordering (often no control), e.g.:
  - greedy scheduling : run a thread as long as possible before context switching (not very concurrent).
  - LIFO scheduling : give priority to newly waiting tasks (starvation).
- Therefore, it is difficult to achieve significant speedup for many algorithms/programs.
- In general, benefit comes when many programs achieve some speedup so there is an overall improvement on a multiprocessor computer.

5.8 Thread Creation

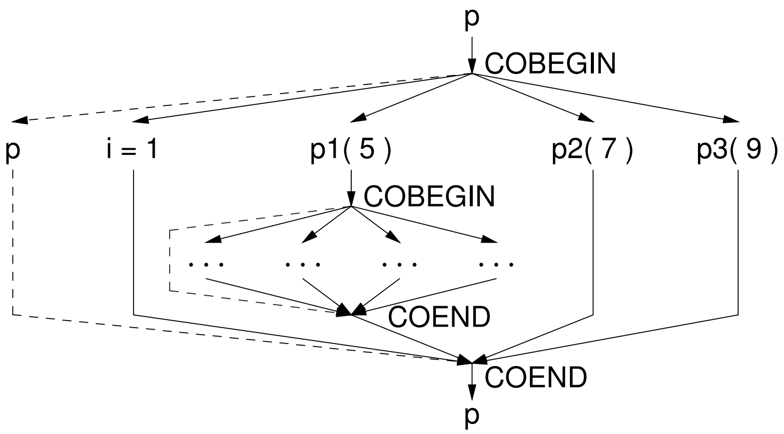
- Concurrency requires 3 mechanisms in a programming language.
  1. creation – cause another thread of control to come into existence.
  2. synchronization – establish timing relationships among threads, e.g., same time, same rate, happens before/after.
  3. communication – transmit data among threads.
- Thread creation must be a primitive operation; cannot be built from other operations in a language.
- ⇒ need new construct to create a thread and define where the thread starts execution.

5.8.1 COBEGIN/COEND

- Compound statement with statements run by multiple threads.

```
#include <uCobegin.h>
int i;
void p1(...);  void p2(...);  void p3(...);
// initial thread creates threads
COBEGIN                // threads execute statement in block
    BEGIN i = 1;   ... END
    BEGIN p1( 5 ); ... END       // order and speed of internal
    BEGIN p2( 7 ); ... END       // thread execution is unknown
    BEGIN p3( 9 ); ... END
COEND                  // initial thread waits for all internal threads to
                       // finish (synchronize) before control continues
```

- Implicit or explicit concurrency?
- A **thread graph** represents thread creations:



- Restricted to creating trees (lattice) of threads.
- Use recursion to create dynamic number of threads.

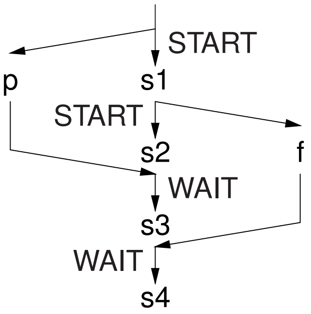
```
void loop( int N ) {
    if ( N != 0 ) {
        COBEGIN
            BEGIN p1( ... ); END
            BEGIN loop( N – 1 ); END // recursive call
        COEND // wait for return of recursive call
    }
}
cin >> N;
loop( N );
```

- What does the thread graph look like?

5.8.2 START/WAIT

- Start thread in routine and wait (join) at thread termination, allowing arbitrary thread graph:

```
#include <uCobegin.h>
int i;
void p( int i ) {...}
int f( int i ) {...}
auto tp = START( p, 5 );
s1  // continue execution, do not wait for p
auto tf = START( f, 8 );
s2  // continue execution, do not wait for f
WAIT( tp ); // wait for p to finish
s3
i = WAIT( tf ); // wait for f to finish
s4
```



- Allows same routine to be started multiple times with different arguments.
- Implicit or explicit concurrency?

- COBEGIN/COEND can only approximate this thread graph:

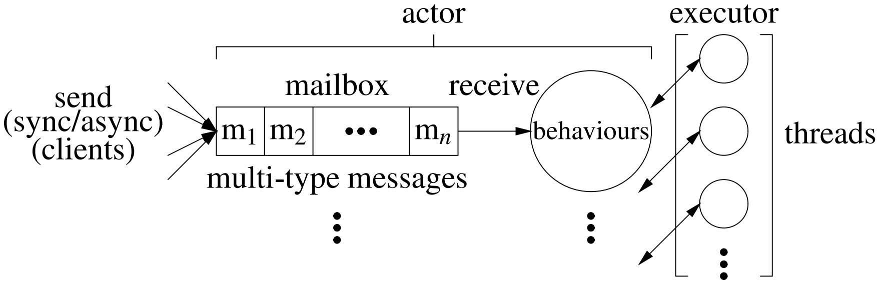
```
COBEGIN
    BEGIN p( 5 ); END
    BEGIN s1;
        COBEGIN
            BEGIN f( 8 ); END
            BEGIN s2; END
        COEND // wait for f!
    END
COEND
s3; s4;
```

- START/WAIT can simulate COBEGIN/COEND:

```
COBEGIN                        auto t1 = START( p1, ... )
    BEGIN p1(...) END          auto t2 = START( p2, ... )
    BEGIN p2(...) END          WAIT t1
COEND                          WAIT t2
```

5.8.3 Actor

- An **actor** (Hewitt/Agha) is a unit of work *without* a thread, like BEGIN/END.



- An executor thread matches an actor with a message and runs the actor's behaviour, like COBEGIN/COEND
- Communication is via polymorphic queue of messages (mailbox) ⇒ dynamic type-checking.
- Usually no shared information among actors and no blocking is allowed.
- Actor systems in popular languages: CAF (C++), ProtoActor (Go), Akka (Scala).
- Must declare messages and actors.

```
#include <uActor.h>
struct StrMsg : public uActor::Message { // derived message
    string val;                          // string message
    StrMsg( string val ) : Message( uActor::Delete ), // delete after use
                           val( val ) {}
};
```

```
_Actor Hello {   // : public uActor
    Allocation receive( Message & msg ) { // receive base type
        iftype( StrMsg, msg ) {         // discriminate derived message
            . . . msg−>val; . . .       // access derived message
        } eliftype ( StrMsg, msg ) return Delete; // delete actor
        endiftype                       // MUST HAVE
        return Nodelete;                // reuse actor
    }
};
int main() {
    uActor::start();                    // start actor system
    *new Hello() | *new StrMsg( "hello" ) | uActor::stopMsg;
    *new Hello() | *new StrMsg( "bonjour" ) | uActor::stopMsg;
    uActor::stop();                     // wait for all actors to terminate
}
```

- Implicit or explicit concurrency?
- Must start actor system (and create thread pool) (**uActor::start()**).
- Actor must receive at least one message to start.
- Messages received in FIFO order from mailbox and executed sequentially by executor.
- Received *derived* message accessed through name *msg*.
- Send messages with operator **|**.
- (StartMsg) uActor::startMsg / (StopMsg) uActor::stopMsg persistent predefined messages.
- Must wait for actors to complete (**uActor::stop()**).
- Each actor *implicitly* inherits from uActor; each message *explicitly* inherits from uActor::Message.

```
class uActor {
  public:
    enum Allocation { Nodelete, Delete, Destroy, Finished }; // allocation actions
    struct Message {
        Allocation allocation;                // allocation action
        . . .
    };
    class SenderMsg : public Message {
        uActor * sender();                    // sender actor
    };
    static struct StartMsg : public uActor::SenderMsg {} startMsg; // start actor
    static struct StopMsg : public uActor::SenderMsg {} stopMsg; // terminate actor
    static void start(); // create executor to run actors
    static bool stop(); // wait for all actors to terminate or timeout
  private:
    Allocation allocation;                    // allocation action
};
```

- Most actor systems leverage garbage collection to manage actors and messages, and the actor system ends after all actors terminate.
- C++ does not have garbage collection so actors/messages use explicit storage-management returning an allocation status for each actor/message.

- After the actor returns, the executor checks what to do with the message and actor.

  Nodelete ⇒ actor/message persists after receive. Use for multi-use actors or messages during their life time. (message default)

  Delete ⇒ actor/message deleted after receive, and decrement actor count. Use with dynamically allocated actors or messages at completion.

  Destroy ⇒ actor/message destructor called after receive, storage not deallocated, and decrement actor count. Use with placement allocated actors or messages at completion.

  Finished ⇒ neither destructor called nor storage deallocated after receive, and decrement actor count. Use with stack allocated actors or messages at completion.

```
#include <uActor.h>
struct StrMsg : public uActor::Message { // default Nodelete
    string val;
    StrMsg( string val ) : val( val ) {}
};
_Actor Hello {
    Allocation receive( Message & msg ) {
        iftype( StrMsg, msg ) {
            . . . msg−>val . . .;
        } endiftype
        return Finished;   // no delete/destroy but remove from actor system
    }
};
int main() {
    uActor::start();
    Hello hellos[2];        // stack allocate actors and messages
    StrMsg hello( "hello" ), bonjour( "bonjour" );
    hellos[0] | hello;
    hellos[1] | bonjour;
    uActor::stop();
} // DEALLOCATE ACTORS/MESSAGES
```

- One shot actor with single string message (no stopMsg).

5.8.4 Thread Object

- C++ is an object-oriented programming language, which suggests:
  - wrap the thread in an object to leverage all class features
  - use object allocation/deallocation to define thread lifetime rather than control structure

```
                _Task T {           // thread type
                    void main() {. . .} // thread starts here
                };
COBEGIN         {                   // { int i, j, k; } ???
                    T t;            // create object on stack, start thread
COEND           }                   // wait for thread to finish

START           T * t = new T;      // create thread object on heap, start thread
WAIT            delete t;           // wait for thread to finish
```

- Block-terminate/delete must wait for each task’s thread to finish. Why?

- Unusual to:
  - create object in a block and not use it
  - allocate object and immediately delete it.
- Simulate COBEGIN/COEND with **_Task** object by creating type for each statement:

```
int i;
_Task T1 {
    void main() { i = 1; }
};
_Task T2 {
    void main() { p1(5); }
};
_Task T3 {
    void main() { p2(7); }
};
_Task T4 {
    void main() { p3(9); }
};
```

```
int main() {
    { // COBEGIN
        T1 t1;  T2 t2;  T3 t3;  T4 t4;
    } // COEND
}
void p1(. . .) {
    { // COBEGIN
        T5 t5;  T6 t6;  T7 t7;  T8 t8;
    } // COEND
}
```

- Simulate START/WAIT with **_Task** object by creating type for each call:

```
int i;
_Task T1 {
    void main() { p(5); }
};
_Task T2 {
    int temp;
    void main() { temp = f(8); }
  public:
    ~T2() { i = temp; }
};
```

```
int main() {
    T1 * tp = new T1;    // start T1
    . . . s1 . . .
    T2 * tf = new T2;    // start T2
    . . . s2 . . .
    delete tp;           // wait for p
    . . . s3 . . .
    delete tf;           // wait for f
    . . . s4 . . .
}
```

- Variable i cannot be assigned until tf is deleted, otherwise the value could change in s2/s3.
- Implicit or explicit concurrency?

5.9 Termination Synchronization

- A thread terminates when:
  - it finishes normally
  - it finishes with an error
  - it is killed by its parent (or sibling) (not supported in μC++)
  - because the parent terminates (not supported in μC++)
- Children can continue to exist even after the parent terminates (although this is rare).
  - E.g. sign off and leave child process(es) running
- Synchronizing at termination is possible for independent threads.
- Termination synchronization may be used to perform a final communication.

5.10 Divide-and-Conquer

- Divide-and-conquer is characterized by ability to subdivide work across data ⇒ work can be performed independently on the data.

- Work performed on each data group is identical to work performed on data as whole (scatter).

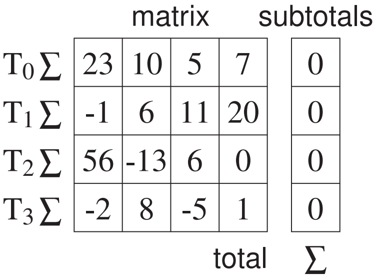
- Taken to extremes, each data item is processed independently, but administration of concurrency becomes greater than cost of work.

- Only termination synchronization is required to know when the work is done (gather).

- Partial results are then processed further if necessary.

- Sum rows of a matrix concurrently using concurrent statement:

```
#include <uCobegin.h>
int main() {
    const int rows = 10, cols = 10;
    int matrix[rows][cols], subtotals[rows], total = 0;
    // read matrix
    COFOR( r, 0, rows,
    // for ( int r = 0; r < rows; r += 1 )
        subtotals[r] = 0;  // r is loop number
        for ( int c = 0; c < cols; c += 1 )
            subtotals[r] += matrix[r][c];
    ); // wait for threads
    for ( int r = 0; r < rows; r += 1 ) {
        total += subtotals[r];  // total subtotals
    }
    cout << total << endl;
}
```



	matrix				subtotals
T_0 Σ	23	10	5	7	0
T_1 Σ	-1	6	11	20	0
T_2 Σ	56	-13	6	0	0
T_3 Σ	-2	8	-5	1	0
				total	Σ

- COFOR *logically* creates end – start threads, indexed start..end – 1 per loop body.

- Implicit or explicit concurrency?

- Sum rows of a matrix concurrently using actors:

```
_Actor Adder {
    int * row, cols, & subtotal;            // communication
    Allocation receive( Message & ) { // only startMsg
        subtotal = 0;
        for ( int c = 0; c < cols; c += 1 ) subtotal += row[c];
        return Delete;                      // delete actor (match new)
    }
  public:
    Adder( int row[ ], int cols, int & subtotal ) : row( row ), cols( cols ), subtotal( subtotal ) {}
};
```

```
int main() {
    . . . // same
    uActor::start();                    // start actor system
    for ( int r = 0; r < rows; r += 1 ) { // actor per row
        *new Adder( matrix[r], cols, subtotals[r] ) | uActor::startMsg;
    }
    uActor::stop();                     // wait for all actors to terminate
    . . . // same
} // main
```

Constructor is a cheat message and may not be allowed.

- Sum rows of a matrix concurrently using concurrent objects:

```
_Task Adder {
    int * row, cols, & subtotal;        // communication
    void main() {
        subtotal = 0;
        for ( int c = 0; c < cols; c += 1 ) subtotal += row[c];
    }
  public:
    Adder( int row[ ], int cols, int & subtotal ) : row( row ), cols( cols ), subtotal( subtotal ) {}
};
int main() {
    . . . // same
    Adder * adders[rows];
    for ( int r = 0; r < rows; r += 1 ) { // start threads to sum rows
        adders[r] = new Adder( matrix[r], cols, subtotals[r] );
    }
    for ( int r = 0; r < rows; r += 1 ) { // wait for threads to finish
        delete adders[r];
        total += subtotals[r];          // total subtotals
    }
    cout << total << endl;
}
int main() {
    . . . // same
    {
        uArrayPtr( Adder, adders, rows );
        for ( int r = 0; r < rows; r += 1 ) { // start threads to sum rows
            adders[r]( matrix[r], cols, subtotals[r] );
        }
    } // wait for tasks to terminate
    for ( int r = 0; r < rows; r += 1 ) {
        total += subtotals[r];  // total subtotals
    }
}
```

- Why create objects in the heap versus stack?
- Does it matter in what order objects are created?
- Does it matter in what order objects are deleted? (critical path)

5.11 Exceptions

- Exceptions can be handled locally within a task, or nonlocally among coroutines, or concurrently among tasks.
    - ◦ All concurrent exceptions are nonlocal, but nonlocal exceptions can also be sequential.
- Local task exceptions are different for coroutines and tasks.
    - ◦ Unhandled exception goes to coroutine's last resumer and task's joiner.
- Nonlocal exceptions are possible because each coroutine/task has its own stack (execution state)
- Nonlocal exceptions between a task and a coroutine are the same as between coroutines (single thread).
- Concurrent exceptions among tasks are more complex due to the multiple threads.
- A concurrent exception provides an additional kind of communication among tasks.
- For example, two tasks may begin searching for a key in different sets:

```
_Exception StopEvent {};
_Task Searcher {
    Searcher * partner;
    void main() {
        try {
            _Enable {                    // allow nonlocal exceptions
                . . .                    // search
                if ( key == . . . ) {    // found result
                    _Resume StopEvent() _At *partner; // stop partner
                    _Throw StopEvent(); // stop me
                }
            }
        } catch( StopEvent ) {. . .}     // reset for next search
```

- When one task finds the key, it informs the other task to stop searching.
- For a concurrent raise, the source execution may only block while queueing the event for delivery at the faulting execution.
- After event is delivered, faulting execution it is not interrupted, it polls:
    - ◦ when an **_Enable** statement begins/ends,
    - ◦ after a call to suspend/resume,
    - ◦ after a call to yield,
    - ◦ after a call to wait,
    - ◦ after a call to **_Accept** unblocks for RendezvousFailure.

  Therefore exception delivery is NOT instantaneous and task continues running.
- Similar to coroutines, see Section 3.7, p. 36, an unhandled exception for a task raises the nonlocal exception uBaseCoroutine::UnhandledException at the task's ***joiner*** and then terminates the task.

```
_Exception E {};
_Task T {
    void main() { _Throw E(); } // unwind
};
int main() {
    try {
        { // extra block
            T t;
        } // continue _CatchResume
    } _CatchResume( uBaseCoroutine::UnhandledException & ) {. . .} // one of
      catch( uBaseCoroutine::UnhandledException & ) {. . .}
    // catch continues after try
}
```

- Forwarding of `UnhandledException` occurs across any number of tasks (and coroutines), until the program main forwards and the program terminates by calling main's `set_terminate`.

5.12 Synchronization and Communication During Execution

- Synchronization occurs when one thread waits until another thread has reached a certain execution point (state and code).
- One place synchronization is needed is in transmitting data between threads.
  - One thread has to be ready to transmit the information and the other has to be ready to receive it, simultaneously.
  - Otherwise one might transmit when no one is receiving, or one might receive when nothing is transmitted.

```
bool Insert = false, Remove = false;
int Data;

_Task Prod {
    int N;
    void main() {
        for ( int i = 1; i <= N; i += 1 ) {
            Data = i;   // transfer data
            Insert = true;
            while ( ! Remove ) {} // busy wait
            Remove = false;
        }
    }
  public:
    Prod( int N ) : N( N ) {}
};
```

```
_Task Cons {
    int N;
    void main() {
        int data;
        for ( int i = 1; i <= N; i += 1 ) {
            while ( ! Insert ) {} // busy wait
            Insert = false;
            data = Data; // remove data
            Remove = true;
        }
    }
  public:
    Cons( int N ) : N( N ) {}
};
int main() {
    Prod prod( 5 ); Cons cons( 5 );
}
```

- 2 infinite loops! No, because of implicit switching between threads.
- `cons` synchronizes (waits) until `prod` transfers data, then `prod` waits for `cons` to remove data.
- A loop waiting for an event among threads is called a **busy wait**.
- Are 2 synchronization flags necessary?

5.13 Communication

- Once threads are synchronized there are many ways that information can be transferred from one thread to the other.
- If the threads are in the same memory, then information can be transferred by value or address (e.g., reference parameter).
- If the threads are not in the same memory (distributed), then transferring information by value is straightforward but by address is difficult.

5.14 Critical Section

- Threads may access non-concurrent objects, like a file or linked-list.
- There is a potential problem if there are multiple threads attempting to operate on the same object simultaneously.
- Not a problem if the operation on the object is **atomic** (not divisible).
- This means no other thread can modify any partial results during the operation on the object (but the thread can be interrupted).
- Where an operation is composed of many instructions, it is often necessary to make the operation atomic.
- A group of instructions on an associated object (data) that must be performed atomically is called a **critical section**.
- Preventing simultaneous execution of a critical section by multiple threads is called **mutual exclusion**.
- Must determine when concurrent access is allowed and when it must be prevented.
- Handle by detecting any sharing and serialize all access.
  - Wasteful if threads are only reading.
- Improve by differentiating between reading and writing
  - allow multiple readers or a single writer; still wasteful as a writer may only write at the end of its usage.
- **Need to minimize the amount of mutual exclusion (i.e., make critical sections as small as possible, Amdahl's law) to maximize concurrency.**

5.15 Static Variables

- **Warning**: static variables in a class are shared among all objects generated by that class.
- These shared variables may need mutual exclusion for correct usage.
- However, a few special cases where **static** variables can be used safely, e.g., task constructor.
- If task objects are generated serially, **static** variables can be used in the constructor.

- E.g., assigning each task is own name:

```
_Task T {
    static int tid;
    string name; // must supply storage
    . . .
  public:
    T() {
        name = "T" + to_string( tid );  // shared read
        setName( name.c_str() );       // name task
        tid += 1;                      // shared write
    }
    . . .
};
int T::tid = 0;     // initialize static variable in .C file
T t[10];            // 10 tasks with individual names
```

- Task constructor is executed by the creating thread, so array constructors executed sequentially.
- This approach only works if one task creates all the objects and initialization data is internal.
- Instead of **static** variables, pass a task identifier to the constructor:

```
T::T( int tid ) { . . . } // constructor naming
T * t[10];                                      uArray( T, t, 10 );
for ( int i = 0; i < 10; i += 1 ) {             for ( int i = 0; i < 10; i += 1 ) {
    t[i] = new T( i ); // individual names          t[i]( i );
}                                               }
```

- In general, avoid using shared **static** variables in a concurrent program.

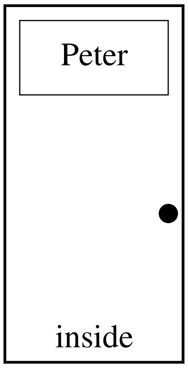
5.16 Mutual Exclusion Game

- Is it possible to write code guaranteeing a statement (or group of statements) is always serially executed by 2 threads?
- Rules of the Game:
  1. Only one thread can be in a critical section at a time with respect to a particular object (**safety**).
  2. Threads may run at arbitrary speed and in arbitrary order, while the underlying system guarantees a thread makes progress (i.e., threads get some CPU time).
  3. If a thread is not in the entry or exit code controlling access to the critical section, it may not prevent other threads from entering the critical section.
  4. In selecting a thread for entry to a critical section, a selection cannot be postponed indefinitely (**liveness**). *Not* satisfying this rule is called **indefinite postponement** or **livelock**.
  5. After a thread starts entry to the critical section, it must eventually enter. *Not* satisfying this rule is called **starvation**.
- **Indefinite postponement and starvation are related by busy waiting.**
- Unlike synchronization, looping for an event in mutual exclusion ***must*** ensure eventual progress.
- Threads waiting to enter can be serviced in any order, as long as each thread eventually enters.

- If threads are *not* serviced in first-come first-serve (FCFS) order of arrival, there is a notion of **unfairness**
- Unfairness implies waiting threads are overtaken by arriving threads, called **barging**.

5.17 Self-Testing Critical Section

```
void CriticalSection() {
    static uBaseTask * curr; // shared
    curr = &uThisTask();
    for ( int i = 1; i <= 100; i += 1 ) {
        . . .                           // work
        if ( curr != &uThisTask() ) {   // check
            abort( "interference" );
        }
    }
}
```

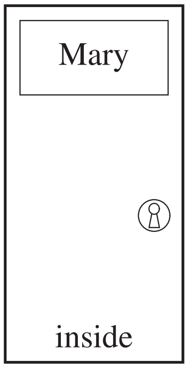


- What is the minimum number of interference tests and where?
- Why are multiple tests useful?

5.18 Software Solutions

5.18.1 Lock

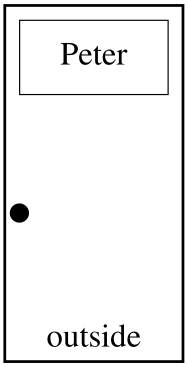
```
enum Yale { CLOSED, OPEN } Lock = OPEN; // shared

_Task PermissionLock {
    void main() {
        for ( int i = 1; i <= 1000; i += 1 ) {
            while ( ::Lock == CLOSED ) {} // entry protocol
            ::Lock = CLOSED;
            CriticalSection();       // critical section
            ::Lock = OPEN;           // exit protocol
        }
    }
  public:
    PermissionLock() {}
};
int main() {
    PermissionLock t0, t1;
}
```



Breaks rule 1

5.18.2 Alternation

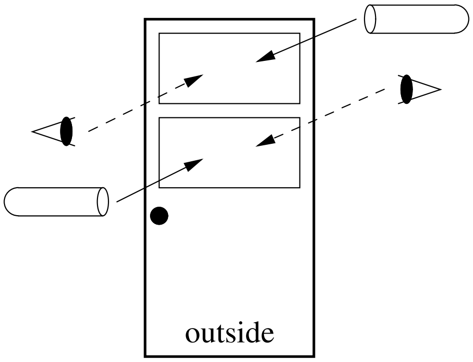
```
int Last = 0;                    // shared

_Task Alternation {
      int me;

      void main() {
            for ( int i = 1; i <= 1000; i += 1 ) {
                  while ( ::Last == me ) {} // entry protocol
                  CriticalSection();        // critical section
                  ::Last = me;              // exit protocol
            }
      }
   public:
      Alternation( int me ) : me( me ) {}
};
int main() {
      Alternation t0( 0 ), t1( 1 );
}
```



Breaks rule 3

5.18.3 Declare Intent

```
enum Intent { WantIn, DontWantIn };

_Task DeclIntent {
      Intent & me, & you;
      void main() {
            for ( int i = 1; i <= 1000; i += 1 ) {
                  me = WantIn;              // entry protocol
                  while ( you == WantIn ) {}
                  CriticalSection();        // critical section
                  me = DontWantIn;          // exit protocol
            }
      }
   public:
      DeclIntent( Intent & me, Intent & you ) :
                   me(me), you(you) {}
};
int main() {
      Intent me = DontWantIn, you = DontWantIn;
      DeclIntent t0( me, you ), t1( you, me );
}
```



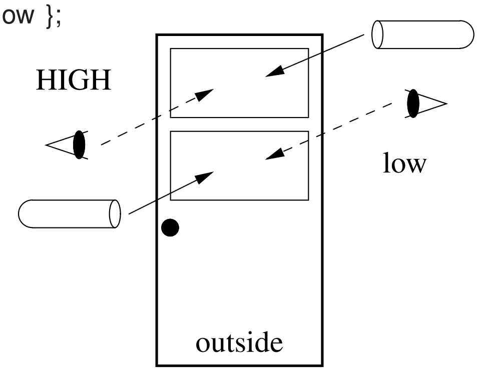
Breaks rule 4

5.18.4 Retract Intent

```
enum Intent { WantIn, DontWantIn };
_Task RetractIntent {
    Intent & me, & you;
    void main() {
        for ( int i = 1; i <= 1000; i += 1 ) {
            for ( ;; ) {                // entry protocol
                me = WantIn;
              if ( you == DontWantIn ) break;
                me = DontWantIn;
                while ( you == WantIn ) {}
            }
            CriticalSection();          // critical section
            me = DontWantIn;            // exit protocol
        }
    }
  public:
    RetractIntent( Intent & me, Intent & you ) : me(me), you(you) {}
};
int main() {
    Intent me = DontWantIn, you = DontWantIn;
    RetractIntent t0( me, you ), t1( you, me );
}
```

Breaks rule 4

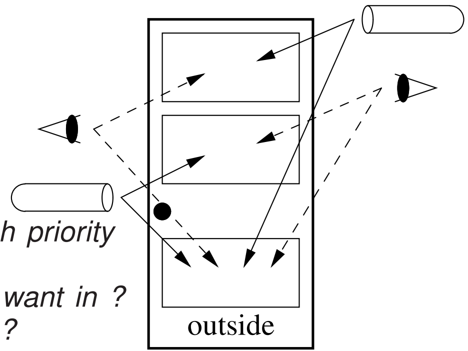
5.18.5 Prioritized Retract Intent



```
enum Intent { WantIn, DontWantIn }; enum Priority { HIGH, low };
_Task PriorityEntry {
    Intent & me, & you;  Priority priority;
    void main() {
        for ( int i = 1; i <= 1000; i += 1 ) {
            for ( ;; ) {                // entry protocol
                me = WantIn;
              if ( you == DontWantIn ) break;
                if ( priority == low ) {
                    me = DontWantIn;
                    while (you == WantIn) {} // busy wait
                }
            }
            CriticalSection();          // critical section
            me = DontWantIn;            // exit protocol
        }
    }
  public:
    PriorityEntry( Priority p, Intent & me, Intent & you ) : priority(p), me(me), you(you) {}
};
int main() {
    Intent me = DontWantIn, you = DontWantIn;
    PriorityEntry t0( HIGH, me, you ), t1( low, you, me );
}
```

Breaks rule 5

5.18.6 Dekker (modified retract intent)



```
enum Intent { WantIn, DontWantIn };
Intent * Last;
_Task Dekker {
    Intent & me, & you;
    void main() {
        for ( int i = 1; i <= 1000; i += 1 ) {
            for ( ;; ) {                    // entry protocol, high priority
                me = WantIn;                // READ FLICKER
              if ( you == DontWantIn ) break; // does not want in ?
                if ( ::Last == &me ) {  // low priority task ?
                    me = DontWantIn; // retract intent, READ FLICKER
                    while ( ::Last == &me // low priority busy wait
                          && you == WantIn ) {}
                }
            }
            CriticalSection();
            if ( ::Last != &me )            // exit protocol
                ::Last = &me;               // READ FLICKER
            me = DontWantIn;                // READ FLICKER
        }
    }
  public:
    Dekker( Intent & me, Intent & you ) : me(me), you(you) {}
};


int main() {
    Intent me = DontWantIn, you = DontWantIn;
    ::Last = &me;           // arbitrary who starts as last
    Dekker t0( me, you ), t1( you, me );
}
```

- Dekker's algorithm appears **RW-safe**.
  - On cheap multi-core computers, read/write is not atomic.
  - Hence, simultaneous writes scramble bits, and for simultaneous read/write, read sees flickering bits during write.
  - RW-safe means a mutual-exclusion algorithm works for non-atomic read/write.
  - Dekker has no simultaneous W/W because intent reset *after* alternation in exit protocol.
  - Dekker has simultaneous R/W but all are equality so works ***if final value never flickers***.

- 2015 Hesselink found two failure case if final values flickers:

1.

T_0	T_1
9 ::Last = &me	
10 me = DontWantIn	
(flicker DontWantIn)	
	3 you == DontWantIn (**true**)
	7 Critical Section
	9 ::Last = &me
(flicker WantIn)	
	3 you == DontWantIn (**false**)
	4 ::Last == &me (**true**)
	6 low priority wait
(flicker DontWantIn)	
terminate	
	6 ::Last == &me (**true**, spin forever)

T_1 spins forever (break rule 4)

2.

T_0	T_1
7 Critical Section	
9 ::Last = &me	
(flicker you T_1)	
	6 ::Last == &me
(flicker me T_0)	
10 me = DontWantIn	
(repeat)	(repeat)

T_1 starvation (break rule 5)

- RW-safe version (**Hesselink**)
  - line 6: add conjunction `you == WantIn`
    ⇒ stop spinning
  - line 8: add conditional assignment to `::Last`
    ⇒ not assigning at line 9 when `::Last != &me` prevents flicker so T_1 makes progress.

- Madness but it works!

```
for ( ;; ) {                                  // entry protocol, high priority
    for ( int i = 0; i < 100; i += 1 ) me = rand() % 2 ? WantIn : DontWantIn;
    me = WantIn;                              // READ FLICKER
  if ( you == DontWantIn ) break;             // does not want in ?
    if ( ::Last == &me ) {                    // low priority task ?
        me = DontWantIn;                      // retract intent, READ FLICKER
        while ( ::Last == &me                 // low priority busy wait
                && you == WantIn ) {
            for ( int i = 0; i < 100; i += 1 ) me = rand() % 2 ? WantIn : DontWantIn;
        }
    }
}
```

```
    CriticalSection();
    for ( int i = 0; i < 100; i += 1 ) ::Last = rand() % 2 ? &me : &you;
    if ( ::Last != &me )                      // exit protocol
        ::Last = &me;                         // READ FLICKER
    for ( int i = 0; i < 100; i += 1 ) me = rand() % 2 ? WantIn : DontWantIn;
    me = DontWantIn;                          // READ FLICKER
```

- Dekker has **unbounded overtaking** (not starvation) because *race loser retracts intent*.
- ⇒ thread exiting critical does not exclude itself for reentry.
  - T0 exits critical section and attempts reentry
  - T1 is now high priority (Last != me) but delays in low-priority busy-loop and resetting its intent.
  - T0 can enter critical section unbounded times until T1 resets its intent
  - T1 sets intent ⇒ bound of 1 as T0 can be entering or in critical section
- Unbounded overtaking is allowed by rule 3: not preventing entry to the critical section by the delayed thread.

5.18.7 Peterson (modified declare intent)

```
enum Intent { WantIn, DontWantIn };
Intent * Last;

_Task Peterson {
    Intent & me, & you;
    void main() {
        for ( int i = 1; i <= 1000; i += 1 ) {
            me = WantIn;            // entry protocol, order matters
            ::Last = &me;           // RACE!
            while ( you == WantIn && ::Last == &me ) {}
            CriticalSection();      // critical section
            me = DontWantIn;        // exit protocol
        }
    }
  public:
    Peterson( Intent & me, Intent & you ) : me(me), you(you) {}
};
int main() {
    Intent me = DontWantIn, you = DontWantIn;
    Peterson t0(me, you), t1(you, me);
}
```

- Peterson's algorithm is RW-**unsafe** requiring atomic read/write operations.
- Peterson has **bounded overtaking** because *race loser does not retracts intent*.
- ⇒ thread exiting critical excludes itself for reentry.
  - T0 exits critical section and attempts reentry
  - T0 runs race by itself and loses
  - T0 must wait (Last == me)
  - T1 eventually sees (Last != me)

- Bounded overtaking allowed by rule 3 because prevention occurs *in the entry protocol*.

- Can line 2 be moved before 1?

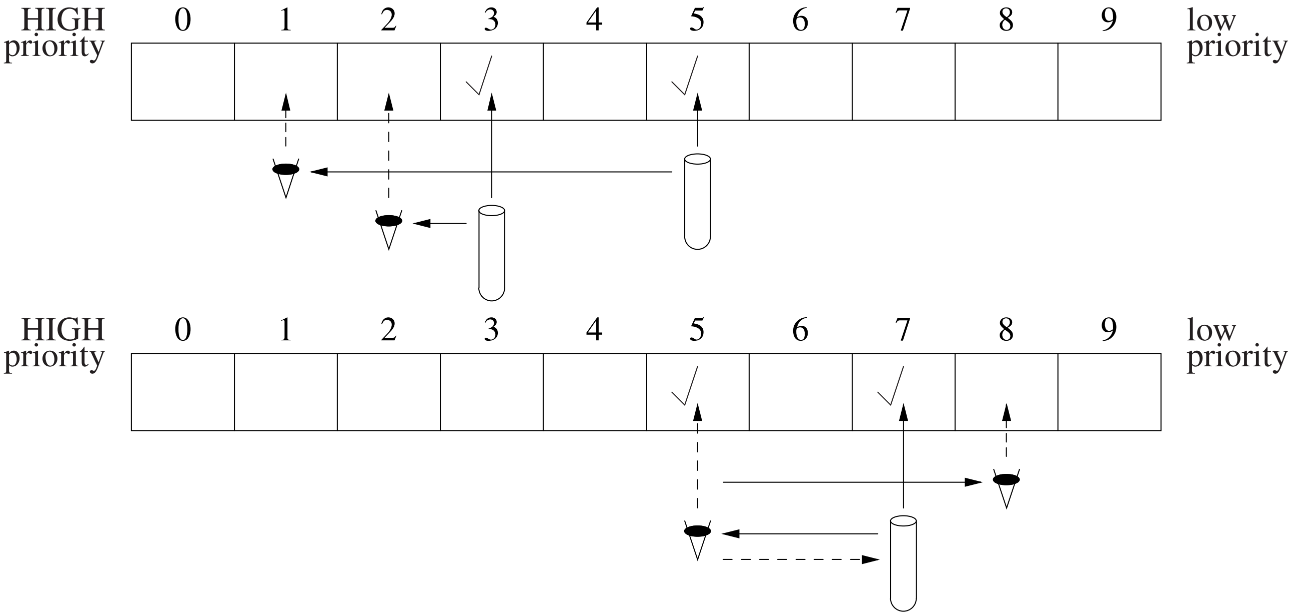
```
1   2   ::Last = &me;                   // RACE!
2   1   me = WantIn;                    // entry protocol
3   3   while ( you == WantIn && ::Last == &me ) {}
4   4   CriticalSection();              // critical section
5   5   me = DontWantIn;                // exit protocol
```

  - ○ T0 executes Line 1 ⇒ `::Last = T0`
  - ○ T1 executes Line 1 ⇒ `::Last = T1`
  - ○ T1 executes Line 2 ⇒ `T1 = WantIn`
  - ○ T1 enters CS, because `T0 == DontWantIn`
  - ○ T0 executes Line 2 ⇒ `T0 = WantIn`
  - ○ T0 enters CS, because `::Last == T1`

5.18.8 N-Thread Prioritized Entry

```
enum Intent { WantIn, DontWantIn };
_Task NTask { // Lamport (simpler version of Burns-Lynch)
    Intent * intents;                          // position & priority
    int N, priority, i, j;
    void main() {
        for ( i = 1; i <= 1000; i += 1 ) {
            // step 1, wait for tasks with higher priority
            do {                               // entry protocol
                intents[priority] = WantIn;
                // check if task with higher priority wants in
                for ( j = priority-1; j >= 0; j -= 1 ) {
                  if ( intents[j] == WantIn ) {
                        intents[priority] = DontWantIn;
                        while ( intents[j] == WantIn ) {}
                        break;
                    }
                }
            } while ( intents[priority] == DontWantIn );

            // step 2, wait for tasks with lower priority
            for ( j = priority+1; j < N; j += 1 ) {
                while ( intents[j] == WantIn ) {}
            }
            CriticalSection();
            intents[priority] = DontWantIn;        // exit protocol
        }
    }
  public:
    NTask( Intent i[ ], int N, int p ) : intents(i), N(N), priority(p) {}
};
```

Breaks rule 5



- Only *N* bits needed.
- No known solution for all 5 rules using only *N* bits.
- Other N-thread solutions use more memory: best: 3-bit RW-unsafe, 4-bit RW-safe.

5.18.9 N-Thread Bakery (Tickets)

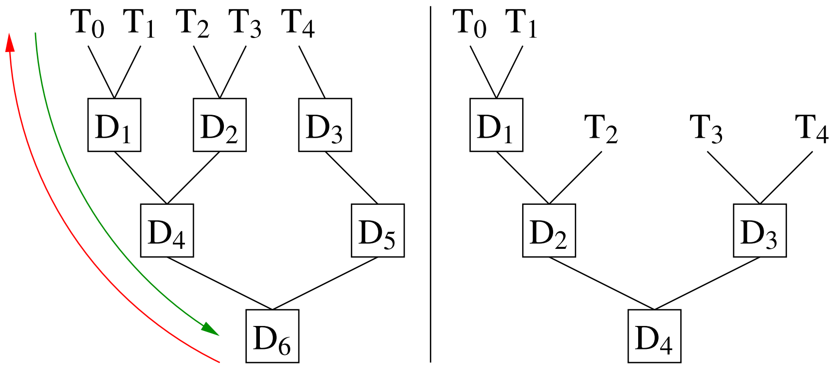
```
_Task Bakery { // (Lamport) Hehner-Shyamasundar
    int * ticket, N, priority;
    void main() {
        for ( int i = 0; i < 1000; i += 1 ) {
            // step 1, select a ticket
            ticket[priority] = 0;            // highest priority
            int max = 0;                     // O(N) search
            for ( int j = 0; j < N; j += 1 ) { //  for largest ticket
                int v = ticket[j];           // can change so copy
                if ( v != INT_MAX && max < v ) max = v;
            }
            max += 1;                        // advance ticket
            ticket[priority] = max;
            // step 2, wait for ticket to be selected
            for ( int j = 0; j < N; j += 1 ) { // check tickets
                while ( ticket[j] < max ||
                  (ticket[j] == max && j < priority) ) {}
            }
            CriticalSection();
            ticket[priority] = INT_MAX;      // exit protocol
        }
    }
  public:
    Bakery( int t[ ], int N, int p ) : ticket(t), N(N), priority(p) {}
};
```

HIGH priority	0	1	2	3	4	5	6	7	8	9	low priority
	∞	∞	17	∞	0	18	18	0	20	19	

- ticket value of ∞ (INT_MAX) ⇒ don't want in
- ticket value of **0** ⇒ selecting ticket
- ticket selection is unusual
- tickets are not unique ⇒ use position as secondary priority
- low ticket and position ⇒ high priority
- ticket values cannot increase indefinitely ⇒ could fail (probabilistically correct)
- ticket value reset to INT_MAX when no attempted entry
- NM bits, where M is the ticket size (e.g., 32 bits)
- Lamport RW-safe
- Hehner/Shyamasundar RW-unsafe
  assignment ticket[priority] = max can flickers to INT_MAX ⇒ other tasks proceed

5.18.10 Tournament

- Binary (d-ary) tree with $\lceil N/2 \rceil$ start nodes and $\lceil \lg N \rceil$ levels.



maximal **minimal**

- Thread assigned to start node, where it begins mutual exclusion process.
- Each node is like a Dekker or Peterson 2-thread algorithm.
- Tree structure tries to find compromise between fairness and performance.
- Exit protocol must retract intents in ***reverse*** order.
- Otherwise race between retracting/released threads along same tree path:
  - T_0 retracts its intent (left) at D_1,
  - T_1 (right) now moves from D_1 to D_4, sets its intent at D_4 (left), and with no competition at D_4 proceeds to D_6 (left),
  - T_0 (left) now retracts the intent at D_4 set by T_1,

  - ○ $T_{2/3}$ continue from D_2, sets its intent at D_4 (right), and with no competition at D_4 (left) proceeds to D_6, which ultimately violates mutual exclusion.

- No overall livelock because each node has no livelock.

- No starvation because each node guarantees progress, so each thread eventually reaches the root.

- Tournament algorithm RW-safety depends on the mutual exclusion algorithm; tree traversal is local to each thread.

- Tournament algorithms have unbounded overtaking as no synchronization among the nodes of the tree.

- For a minimal binary tree, the tournament approach uses $(N-1)M$ bits, where $(N-1)$ is the number of tree nodes and M is the node size (e.g., intent, turn).

```
_Task TournamentMax { // Taubenfeld-Buhr
    struct Token { int intents[2], turn; };     // intents/turn
    static Token ** t;                          // triangular matrix
    int depth, id;

    void main() {
        unsigned int lid;                       // local id at each tree level
        for ( int i = 0; i < 1000; i += 1 ) {
            lid = id;                           // entry protocol
            for ( int lv = 0; lv < depth; lv += 1 ) {
                binary_prologue( lid & 1, &t[lv][lid >> 1] );
                lid >>= 1;                      // advance local id for next tree level
            }
            CriticalSection( id );
            for ( int lv = depth - 1; lv >= 0; lv -= 1 ) { // exit protocol
                lid = id >> lv;                 // retract reverse order
                binary_epilogue( lid & 1, &t[lv][lid >> 1] );
            }
        }
    }
  public:
    TournamentMax( struct Token * t[], int depth, int id ) : t( t ), depth( depth ), id( id ) {}
};
```

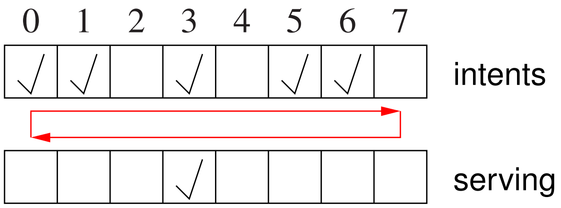
- Can be optimized to 3 shifts and exclusive-or using Peterson 2-thread for binary.

- Path from leaf to root is fixed per thread ⇒ table lookup possible using max or min tree.

5.18.11 Arbiter

- Create full-time arbitrator task to control entry to critical section.

```
bool intents[N], serving[N];            // initialize to false

_Task Client {
    int me;
    void main() {
        for ( int i = 0; i < 100; i += 1 ) {
            intents[me] = true;         // entry protocol
            while ( ! serving[me] ) {} // busy wait
            CriticalSection();
            serving[me] = false;        // exit protocol
        }
    }
  public:
    Client( int me ) : me( me ) {}
};
_Task Arbiter {
    void main() {
        int i = N;                      // force cycle to start at id=0
        for ( ;; ) {
            do {                        // circular search => no starvation
                i = (i + 1) % N;        // advance next client
            } while ( ! intents[i] );   // not want in ?
            intents[i] = false;         // retract intent on behalf of client
            serving[i] = true;          // wait for exit from critical section
            while ( serving[i] ) {}     // busy wait
        }
    }
};
```



- Mutual exclusion becomes synchronization between arbiter and clients.
- Arbiter never uses the critical section ⇒ no indefinite postponement.
- Arbiter cycles through waiting clients (**not FCFS**) ⇒ no starvation.
- RW-unsafe due to read flicker.
- Cost is creation, management, and execution (continuous busy waiting) of arbiter task.

5.19 Hardware Solutions

- Software solutions to the critical-section problem rely on
  - shared information,
  - communication among threads,
  - (maybe) atomic memory-access.

- Hardware solutions introduce level below software level.
- Cheat by making assumptions about execution impossible at software level.
  E.g., control order and speed of execution.
- Allows elimination of much of the shared information and the checking of this information required in the software solution.
- Special instructions to perform an **atomic read and write operation**.
- Sufficient for multitasking on a single CPU.

5.19.1 Test/Set Instruction

- Simple lock of critical section fails:

```
int Lock = OPEN;                // shared
// each task does
while ( Lock == CLOSED );       // fails to achieve (read)
Lock = CLOSED;                  // mutual exclusion (write)
// critical section
Lock = OPEN;
```

- The test-and-set instruction performs an atomic read and fixed assignment.

```
int Lock = OPEN; // shared
```

```
int TestSet( int & b ) {
    // begin atomic
    int temp = b;
    b = CLOSED;
    // end atomic
    return temp;
}
```

```
void Task::main() { // each task does
    while( TestSet( Lock ) == CLOSED );
    // critical section
    Lock = OPEN;
}
```

  - if test/set returns open ⇒ loop stops and lock is set to closed
  - if test/set returns closed ⇒ loop executes until the other thread sets lock to open

- Works for N threads attempting entry to critical section and only depends on one shared datum (lock).
- However, rule 5 is broken, as there is no guarantee of eventual progress.
- In multiple CPU case, hardware (bus) must also guarantee multiple CPUs cannot interleave these special R/W instructions on same memory location.

5.19.2 Swap Instruction

- The swap instruction performs an atomic interchange of two separate values.

```
int Lock = OPEN; // shared
```

```
void Swap( int & a, & b ) {
    int temp;
    // begin atomic
    temp = a;
    a = b;
    b = temp;
    // end atomic
}
```

```
void Task::main() { // each task does
    int dummy = CLOSED;
    do {
        Swap( Lock, dummy );
    } while( dummy == CLOSED );
    // critical section
    Lock = OPEN;
}
```

- if dummy returns open ⇒ loop stops and lock is set to closed
- if dummy returns closed ⇒ loop executes until the other thread sets lock to open

5.19.3 Fetch and Increment Instruction

- The fetch-and-increment instruction performs an increment between the read and write.

```
int Lock = 0; // shared
```

```
int FetchInc( int & val ) {
    // begin atomic
    int temp = val;
    val += 1;
    // end atomic
    return temp;
}
```

```
void Task::main() { // each task does
    while ( FetchInc( Lock ) != 0 );
    // critical section
    Lock = 0;
```

- Often fetch-and-increment is generalized to add any value ⇒ decrement with negative value.
- Lock counter can overflow during busy waiting and starvation (rule 5).
- Use ticket counter to solve both problems (Bakery Algorithm, see Section 5.18.9, p. 87):

```
class ticketLock {
    unsigned int tickets, serving;
  public:
    ticketLock() : tickets( 0 ), serving( 0 ) {}
    void acquire() {                             // entry protocol
        int ticket = FetchInc( tickets );        // obtain a ticket
        while ( ticket != serving ) {}           // busy wait
    }
    void release() {                             // exit protocol
        serving += 1;
    }
};
```

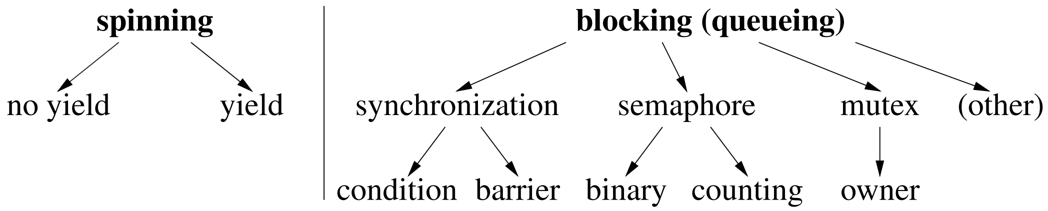
- Equality test works with overflow.
- Ticket overflow only a problem if all values used simultaneously ⇒ $2^N + 1$ tasks, and FIFO service ⇒ no starvation.

6 Locks

- Package software/hardware locking into abstract type for general use.
- Locks are constructed for synchronization or mutual exclusion or both.

6.1 Lock Taxonomy

- Lock implementation is divided into two general categories: spinning and blocking.



- Spinning locks busy wait until an event occurs ⇒ task oscillates between ready and running states due to time slicing.
- Blocking locks do not busy wait, but block until an event occurs ⇒ **some *other* mechanism must unblock waiting task when the event happens**.
- Within each category, different kinds of spinning and blocking locks exist.

6.2 Spin Lock

- A **spin lock** is implemented using busy waiting, which loops checking for an event to occur.

```
while( TestSet( Lock ) == CLOSED );  // use up time-slice (no yield)
```

- So far, when a task is busy waiting, it loops until:
  - critical section becomes unlocked or an event happens.
  - waiting task is preempted (time-slice ends) and put back on ready queue.

  Hence, CPU is wasting time constantly checking the event.
- To increase uniprocessor efficiency, a task can:
  - explicitly terminate its time-slice
  - move back to the ready state after only ***one*** event-check fails. (Why one?)
- Task member yield relinquishes time-slice by *rescheduling* running task back onto ready queue.

```
while( TestSet( Lock ) == CLOSED ) uThisTask().yield(); // relinquish time-slice
```

- To increase multiprocessor efficiency, a task can yield after N event-checks fail. (Why N?)
- Some spin-locks allow adjustment of spin duration, called **adaptive spin-lock**.
- Most spin-lock implementations break rule 5, i.e., no bound on service. ⇒ possible starvation of one or more tasks.
- Spin lock is appropriate and necessary in situations where there is no other work to do.

6.2.1 Implementation

- μC++ provides a non-yielding spin lock, uSpinLock, and a yielding spin lock, uLock.

```
class uSpinLock {
  public:
    uSpinLock(); // open
    void acquire();
    bool tryacquire();
    void release();
};
```

```
class uLock {
  public:
    uLock( unsigned int value = 1 );
    void acquire();
    bool tryacquire();
    void release();
};
```

- Both locks are built directly from an atomic hardware instruction.
- Lock starts closed (0) or opened (1); waiting tasks compete to acquire lock after release.
- In theory, starvation could occur; in practice, it is seldom a problem.
- tryacquire makes one attempt to acquire the lock, i.e., it does not wait.
- It is *not* meaningful to read or to assign to a lock variable, or copy a lock variable, e.g., pass it as a value parameter.
- synchronization

```
_Task T1 {
    uLock & lk;
    void main() {
        . . .
        S1
        lk.release();
        . . .
    }
  public:
    T1( uLock & lk ) : lk(lk) {}
};
```

```
_Task T2 {
    uLock & lk;
    void main() {
        . . .
        lk.acquire();
        S2
        . . .
    }
  public:
    T2( uLock & lk ) : lk(lk) {}
};
```

```
int main() {
    uLock lock( 0 ); // closed
    T1 t1( lock );
    T2 t2( lock );
}
```

- mutual exclusion

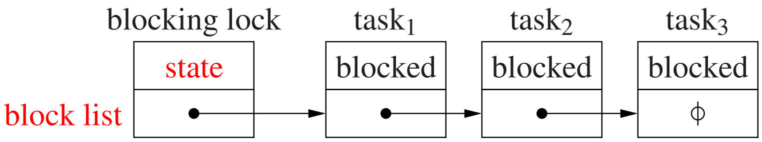
```
_Task T {
    uLock & lk;
    void main() {
        . . .
        lk.acquire();
        // critical section
        lk.release();
        . . .
        lk.acquire();
        // critical section
        lk.release();
        . . .
    }
  public:
    T( uLock & lk ) : lk(lk) {}
};
```

```
int main() {
    uLock lock( 1 ); // open
    T t0( lock ), t1( lock );
}
```

- Does this solution afford maximum concurrency?
- Depends on critical sections: **independent** (disjoint) or **dependent**.
- How many locks are needed for mutual exclusion?

6.3 Blocking Locks

- For spinning locks,
  - acquiring task(s) is solely responsible for detecting an open lock after the releasing task opens it.
- For blocking locks,
  - acquiring task makes ***one*** check for open lock and blocks
  - releasing task has sole responsibility for detecting blocked acquirer and transferring lock, or just releasing lock.
- Blocking locks reduce busy waiting by having releasing task do additional work: **cooperation**.
  - What advantage does the releasing task get from doing the cooperation?
- Therefore, all blocking locks have
  - state to facilitate lock semantics
  - list of blocked acquirers



- Which task is scheduled next from the list of blocked tasks?

6.3.1 Mutex Lock

- **Mutex lock** is used solely to provide mutual exclusion.
- Restricting a lock to just mutual exclusion:

  - separates lock usage between synchronization and mutual exclusion
  - permits optimizations and checks as the lock only provides one specialized function

- Mutex locks are divided into two kinds:
  - **single acquisition** : task that acquired the lock cannot acquire it again
  - **multiple acquisition** : lock owner can acquire it multiple times, called an **owner lock**
- Multiple acquisition can handle looping or recursion involving a lock:

```
void f() {
    . . .
    lock.acquire();
    . . . f();         // recursive call within critical section
    lock.release();
}
```

- May require only one release to unlock, or as many releases as acquires.

6.3.1.1 Implementation

- Multiple acquisition lock manages owner state (**blue**).

```
class MutexLock {
    bool avail;                  // resource available ?
    Task * owner                 // lock owner
    queue<Task> blocked;         // blocked tasks
    SpinLock lock;               // mutex nonblocking lock
  public:
    MutexLock() : avail( true ), owner( nullptr ) {}
    void acquire() {
        lock.acquire();          // barging
        while ( ! avail && owner != currThread() ) { // busy waiting
            // add self to lock's blocked list
            yieldNoSchedule();   // do not reschedule to ready queue
            lock.acquire();      // reacquire spinlock
        }
        avail = false;
        owner = currThread();    // set new owner
        lock.release();
    }
    void release() {
        lock.acquire();
        if ( owner != currThread() ) . . . // ERROR CHECK
        owner = nullptr;         // no owner
        if ( ! blocked.empty() ) {
            // remove task from blocked list and make ready
        }
        avail = true;            // reset
        lock.release();          // RACE
    }
};
```

- yieldNoSchedule yields the processor time-slice but does not reschedule thread to ready queue.
- Single or multiple unblock for multiple acquisition?

- `avail` is necessary as queue can be empty but critical section occupied.

- Problem: **blocking occurs holding spin lock!**

- ⇒ release lock before blocking

```
// add self to blocked list of lock
lock.release();          // allow releasing task to unblock next waiting task
// PREEMPTION ⇒ put on ready queue
yieldNoSchedule();
```

- **Race between blocking and unblocking tasks.**

- Blocking task releases spin lock but preempted *before* yield and put onto ready queue.

- Unblocking task can enter, see blocking task on lock's blocked list, and put on ready queue.

- But task is still on the ready queue because of the preemption!

- Need ***magic*** to atomically yield without scheduling ***and*** release spin lock.

- Magic is often accomplished with more cooperation:

```
yieldNoSchedule( lock );
```

- Spin lock is passed to the runtime system, which does the yield without schedule and then, on behalf of the user thread, unlocks the lock.

- Alternative approach is park/unpark, where each thread blocks on a private binary semaphore (see Section 6.4.4.6, p. 124 private semaphore).

- Disabling and enabling interrupts is too expense.

- Note, the runtime system violates order and speed of execution by being non-preemptable.

- Problem: `avail` and `lock` reset ⇒ acquiring tasks can **barge** ahead of released task.

- Released task must check again (**`while`**) ⇒ busy waiting ⇒ starvation

- **Barging avoidance** (cooperation): hold `avail` between releasing and unblocking task (bounded overtaking).

```
void acquire() {
    lock.acquire();                 // barging
    if ( ! avail && owner != currThread() ) { // avoid barging
        // add self to lock's blocked list
        yieldNoSchedule( lock );    // lock release
        lock.acquire();             // IN GENERAL, reacquire
    } else {
        avail = false;
    }
    owner = currThread();           // set new owner, may not be safe
    lock.release();
}
void release() {
    lock.acquire();
    owner = nullptr;                // no owner
    if ( ! blocked.empty() ) {
        // remove task from blocked list and make ready
    } else {
        avail = true;               // conditional reset
    }
    lock.release();                 // RACE
}
```

- Bargers enter mutual-exclusion protocol but block so released task does not busy wait (**if** rather than **while**).

- Mutual exclusion is ***conceptually passed*** from releasing to unblocking tasks (baton passing).

- If signalled task does not reacquire the spinlock, there can be a race, e.g., owner is read/written simultaneously.

- Because a spinlock is unfair, an infinite stream of bargers can prevent the released task from acquiring the spinlock (short/long-term starvation).

- **Barging prevention** (cooperation): hold lock between releasing and unblocking task (bounded overtaking).

```
void acquire() {
    lock.acquire();                 // prevention barging
    if ( ! avail && owner != currThread() ) {
        // add self to lock's blocked list
        yieldNoSchedule( lock );
        // DO NOT REACQUIRE LOCK
    } else avail = false;
    owner = currThread();           // set new owner
    lock.release();
}
```

```
    void release() {
        lock.acquire();
        owner = nullptr;            // no owner
        if ( ! blocked.empty() ) {
            // remove task from blocked list and make ready
            // DO NOT RELEASE LOCK
        } else {
            avail = true;           // conditional reset
            lock.release();         // NO RACE
        }
    }
```

- **Critical section is not bracketed by the spin lock when lock is passed.**
- Alternative (cooperation): leave lock owner at front of blocked list to act as availability and owner variable.

```
class MutexLock {
        queue<Task> blocked;        // blocked tasks
        SpinLock lock;              // nonblocking lock
    public:
        void acquire() {
            lock.acquire();         // prevention barging
            if ( blocked.empty() ) {   // no one waiting ?
                node.owner = currThread();
                // add self to lock's blocked list
            } else if ( blocked.head().owner != currThread() ) { // not owner ?
                // add self to lock's blocked list
                yieldNoSchedule( lock );
                // DO NOT REACQUIRE LOCK
            }
            lock.release();
        }
        void release() {
            lock.acquire();
            // REMOVE TASK FROM HEAD OF BLOCKED LIST
            if ( ! blocked.empty() ) {
                // MAKE TASK AT FRONT READY BUT DO NOT REMOVE
                // DO NOT RELEASE LOCK
            } else {
                lock.release();     // NO RACE
            }
        }
};
```

- If critical section acquired, blocked list must have a node on it to check for in-use.

6.3.1.2 uOwnerLock

- µC++ provides a multiple-acquisition mutex-lock, uOwnerLock:

```
class uOwnerLock {
  public:
    uOwnerLock();
    uBaseTask * owner();
    unsigned int times();
    void acquire();
    bool tryacquire();
    void release();
};
```

- `owner()` returns **nullptr** if no owner, otherwise address of task that currently owns lock.
- `times()` returns number of times lock has been acquired by owner task.
- Must release as many times as acquire.
- Otherwise, operations same as for `uLock` but with blocking instead of spinning for `acquire`.

6.3.1.3 Mutex-Lock Release-Pattern

- To ensure a mutual exclusion lock is always released use the following patterns.
  - executable statement – finally clause

```
uOwnerLock lock;
lock.acquire();
try {
    . . .                    // protected by lock
} _Finally {
    lock.release();
}
```

  - allocation/deallocation (RAII – Resource Acquisition Is Initialization)

```
class RAII {                 // create once
    uOwnerLock & lock;
  public:
    RAII( uOwnerLock & lock ) : lock( lock ) { lock.acquire(); }
    ~RAII() { lock.release(); }
};
uOwnerLock lock;
{
    RAII raii( lock );       // lock acquired by constructor
    . . .                    // protected by lock
}                            // lock release by destructor
```

- Lock always released on normal, local transfer (**break**/**return**), and exception.
- Cannot be used for barging prevention. Why?

6.3.1.4 Stream Locks

- Specialized mutex lock for I/O based on `uOwnerLock`.
- Concurrent use of C++ streams can produce unpredictable results.
  - if two tasks execute:

```
task₁ : cout << "abc " << "def " << endl;
task₂ : cout << "uvw " << "xyz " << endl;
```

any of the outputs can appear:

```
abc def  | abc uvw xyz | uvw abc xyz def | abuvwc dexf | uvw abc def
uvw xyz  | def         |                 | yz          | xyz
```

- μC++ provides: `osacquire` for output streams and `isacquire` for input streams.

- Most common usage is to create an anonymous stream lock for a cascaded I/O expression:

```
task₁ : osacquire( cout ) << "abc " << "def " << endl;
task₂ : osacquire( cout ) << "uvw " << "xyz " << endl;
```

constraining the output to two different lines in either order:

```
abc def | uvw xyz
uvw xyz | abc def
```

- Multiple I/O statements can be protected using block structure:

```
{   // acquire the lock for stream cout for block duration
    osacquire acq( cout ); // named stream lock
    cout << "abc";
    osacquire( cout ) << "uvw " << "xyz " << endl; // OK?
    cout << "def";
}   // implicitly release the lock when "acq" is deallocated
```

- Which *locking-release* pattern is used by stream locks?

6.3.2 Synchronization Lock

- **Synchronization lock** is used solely to block tasks waiting for synchronization.

- Weakest form of blocking lock as its only state is list of blocked tasks.
  - ⇒ ***acquiring task always blocks*** (no state to make it conditional)
    Need ability to yield time-slice and block versus yield and go back on ready queue.
  - ⇒ ***release is lost when no waiting task*** (no state to remember it)

- Often called a **condition lock**, with wait / signal(notify) for acquire / release.

6.3.2.1 Implementation

- Like mutex lock, synchronization lock needs mutual exclusion for safe implementation.

- Location of mutual exclusion classifies synchronization lock:

  external locking use an external lock to protect task list,

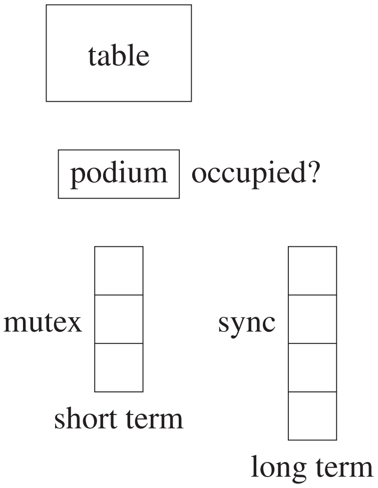
  internal locking use an internal lock to protect state (lock is extra state).

- external locking

```
class SyncLock {
        Task * list;
    public:
        SyncLock() : list( nullptr ) {}
        void acquire() {
            // add self to task list
            yieldNoSchedule();
        }
        void release() {
            if ( list != nullptr ) {
                // remove task from blocked list and make ready
            }
        }
};
```

  - Use external state to avoid lost release.
  - Need mutual exclusion to protect task list and possible external state.
  - Releasing task detects a blocked task and performs necessary cooperation.

- Usage pattern:
  - Cannot enter a restaurant if all tables are full.
  - Must acquire a lock to check for an empty table because state can change.
  - If no free table, block until a table becomes available or **leave** (balk) and eat elsewhere.



- Why is a single waiting queue (bench) inadequate?

```
// shared variables
    MutexLock m;               // external mutex lock
    SyncLock s;                // synchronization lock
    bool occupied = false;     // indicate if event has occurred
// acquiring task
    m.acquire();               // mutual exclusion to examine state & possibly block
    if ( occupied ) {          // event not occurred ?
        if ( /* do not wait */ ) { m.release(); /* go elsewhere */ }
        s.acquire();           // long-term block for event
        m.acquire();           // require mutual exclusion to set state
    }
    occupied = true;           // set
    m.release();
... EAT! ...
// releasing task
    m.acquire();               // mutual exclusion to examine state
    occupied = false;          // reset
    s.release();               // possibly unblock waiting task
    m.release();               // release mutual exclusion
```

- **Blocking occurs holding external mutual-exclusion lock!**
- ⇒ release lock before blocking by modifying synchronization-lock `acquire`.

```
void SyncLock::acquire( MutexLock & m ) { // add parameter
    // add self to task list
    m.release();               // release external mutex-lock
    // PREEMPTION ⇒ put on ready queue
    yieldNoSchedule();
    // possibly reacquire mutexlock
}
```

- **As before, preemption results in race between blocking and unblocking tasks.**
- To prevent race, need to cooperate with scheduler.

```
void SyncLock::acquire( MutexLock & m ) {
    // add self to task list
    yieldNoSchedule( m ); // scheduler unlocks m
    // possibly reacquire mutexlock
}
```

- Or, protecting mutex-lock is bound at synchronization-lock creation and used implicitly.
- Now use first usage pattern.

```
// acquiring task
    m.acquire();               // mutual exclusion to examine state & possibly block
    if ( occupied ) {          // event not occurred ?
        if ( /* do not wait */ ) { m.release(); /* go elsewhere */ }
        s.acquire( m );        // block for event and release mutex lock
        . . .
```

- Has the race been prevented?
- Problem: barging can occur when releasing task resets `occupied`.
  - ⇒ non-FIFO order and possible starvation

- Note, same problems as inside mutex lock but occurring ***outside*** between mutex and synchronization locks.

- Use barging avoidance:

```
// releasing task
    m.acquire();               // mutual exclusion to examine state
    if ( ! s.empty() ) s.release(); // unblock, no reset
    else occupied = false;     // reset
    m.release();               // release mutual exclusion
```

  or prevention:

```
// releasing task
    m.acquire();               // mutual exclusion to examine state
    if ( ! s.empty() ) s.release(); // unblock, no reset
    else { occupied = false; m.release(); } // reset & release
```

- internal locking

```
class SyncLock {
    Task * list;           // blocked tasks
    SpinLock lock;         // internal lock
  public:
    SyncLock() : list( nullptr ) {}
    void acquire( MutexLock & m ) {  // optional external lock
        lock.acquire();
        // add self to task list
        m.release();      // release external mutex-lock
        CAN BE INTERRUPTED HERE
        yieldNoSchedule( lock );
        m.acquire();      // possibly reacquire after blocking
    }
    void release() {
        lock.acquire();
        if ( list != nullptr ) {
            // remove task from blocked list and make ready
        }
        lock.release();
    }
};
```

  - Why does acquire still take an external lock?
  - Why is the race after releasing the external mutex-lock not a problem?

- Has the busy wait been removed from the blocking lock?

6.3.2.2 uCondLock

- μC++ provides an internal synchronization-lock, uCondLock.

```
class uCondLock {
  public:
    uCondLock();
    void wait( uOwnerLock & lock );
    bool signal();
    bool broadcast();
    bool empty();
};
```

- wait/signal block a thread on and unblock a thread from a condition queue, respectively.
- wait atomically blocks the calling task and **releases argument owner-lock**.
- **wait reacquires its argument owner-lock before returning.**
- signal unblocks a single task in FIFO order.
- broadcast unblocks all waiting tasks.
- signal/broadcast do nothing for an empty condition and return false; otherwise, return true.
- empty returns **false** if blocked tasks on the queue and **true** otherwise.

6.3.2.3 Programming Pattern

- Using synchronization locks is complex because they are weak.
- Must provide external mutual-exclusion and protect against loss signal (release).
- Why is synchronization more complex for blocking locks than spinning (uLock)?

```
bool done = false;
```

```
_Task T1 {
    uOwnerLock & mlk;
    uCondLock & clk;
    void main() {
        mlk.acquire();    // prevent lost signal
        if ( ! done )     // signal occurred ?
            // signal not occurred
            clk.wait( mlk ); // atomic wait/release
            // mutex lock re-acquired after wait
        mlk.release();    // release either way
        S2;
    }
  public:
    T1( uOwnerLock & mlk,
        uCondLock & clk ) :
        mlk(mlk), clk(clk) {}
};
```

```
_Task T2 {
    uOwnerLock & mlk;
    uCondLock & clk;
    void main() {
        S1;
        mlk.acquire();    // prevent lost signal
        done = true;      // remember signal occurred
        clk.signal();     // signal lost if not waiting
        mlk.release();
    }
  public:
    T2( uOwnerLock & mlk,
        uCondLock & clk ) :
        mlk(mlk), clk(clk) {}
};
```

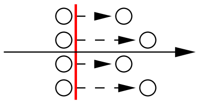
```
int main() {
    uOwnerLock mlk;
    uCondLock clk;
    T1 t1( mlk, clk );
    T2 t2( mlk, clk );
}
```

6.3.3 Barrier

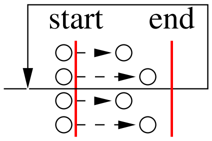
- A **barrier** coordinates a group of tasks performing a concurrent operation surrounded by sequential operations.
- Hence, a barrier is for (gather) synchronization and cannot build mutual exclusion.
- Two kinds of barrier: threads equal group size (T == G) or threads greater than group size (T > G).
- Unlike previous synchronization locks, a ***barrier retains state about the events it manages***: number of tasks blocked on the barrier.
- Since manipulation of this state requires mutual exclusion, most barriers use internal locking.
- E.g., 3 tasks must execute a section of code in a particular order: S1, S2 and S3 must *all* execute before S5, S6 and S7.

```
T1::main() {        T2::main() {        T3::main() {
    . . .               . . .               . . .
    S1                  S2                  S3
    b.block();          b.block();          b.block(); // gather
    S5                  S6                  S7
    . . .               . . .               . . .
}                   }                   }
int main() {
    Barrier b( 3 );
    T1 x( b );
    T2 y( b );
    T3 z( b );
}
```

- Barrier is initialized to control 3 tasks and passed to each task by reference (not copied).
- Barrier blocks each task at call to block until all tasks have called block.
- Last task to call block does not block and releases other tasks (cooperation).
- Hence, all tasks leave together (synchronized) after arriving at the barrier.
- Note, must specify in advance total number of block operations before tasks released.
- Two common uses for barriers:



one shot



cyclic

```
Barrier start( G + 1 ), end( G + 1 ); // shared
Coordinator                                   Workers
// start G tasks so they can initialize
// general initialization                     // initialize
start.block(); // wait for threads to start   start.block(); // wait for threads to start
// do other work                              // do work
end.block();  // wait for threads to end      end.block();  // wait for threads to end
// general close down and possibly loop       // close down
```

- Two barriers allow Coordinator to accumulate results (subtotals) while Workers reinitialize (read next row).
- Alternative is last Worker does coordination, but prevents Workers reinitializing during coordination.
- Why not use termination synchronization and create new tasks for each computation?
  - creation and deletion of computation tasks is expensive
- Incorrectly managing the barrier cycles is called the **reinitialization problem**.

6.3.3.1 Fetch Increment Barrier

- spinning, T == G, flag ensures waiting threads exit barrier even if fast threads change count.

```
struct Barrier {
    size_t group = 0;
    volatile bool flag = false;
    volatile size_t count = 0;
};
void block( Barrier & b ) {
    size_t negflag = ! b.flag;
    if ( FetchInc( b.count, 1 ) < b.group - 1 ) {
        await( b.flag == negflag ); // spin
    } else {
        // SAFE ACTION BEFORE TRIGGERING BARRIER
        b.count = 0;
        b.flag = negflag;
    }
}
```

- Construct failure scenario for `await( b.count == 0 )`.

6.3.3.2 uBarrier

- μC++ barrier is a blocking, T > G, barging-prevention coroutine, where the coroutine main can be resumed by the last task arriving at the barrier.

```
#include <uBarrier.h>
_Cormonitor uBarrier {                          // think _Coroutine
  protected:
    void main() { for ( ;; ) suspend(); }      // points of synchronization
    virtual void last() { resume(); }          // called by last task to barrier
  public:
    uBarrier( unsigned int total );
    unsigned int total() const;                // # of tasks synchronizing
    unsigned int waiters() const;              // # of waiting tasks
    void reset( unsigned int total );          // reset # tasks synchronizing
    virtual void block(); // wait for Gth thread, which calls last, unblocks waiting thread
};
```

- Member `last` is called by the Gth (last) task to the barrier, and then all blocked tasks are released.
- `uBarrier` has implicit mutual exclusion ⇒ no barging ⇒ only manages synchronization
- User barrier is built by:

- ○ inheriting from uBarrier
- ○ redefining last and/or block member and possibly coroutine main
- ○ possibly initializing main from constructor

- E.g., previous matrix sum (see page 74) adds subtotals in order of task termination, but barrier can add subtotals in order produced.

```
_Cormonitor Accumulator : public uBarrier {
        int total_ = 0, temp;
        uBaseTask * Gth_ = nullptr;
    protected:
        void last() {   // reset and remember Gth task
            temp = total_; total_ = 0;
            Gth_ = &uThisTask();
        }
    public:
        Accumulator( int rows ) : uBarrier( rows ) {}
        void block( int subtotal ) {
                total_ += subtotal;
                uBarrier::block();
        }
        int total() { return temp; }
        uBaseTask * Gth() { return Gth_; }
};
_Task Adder {
        int * row, size;
        Accumulator & acc;
        void main() {
                int subtotal = 0;
                for ( unsigned int r = 0; r < size; r += 1 ) subtotal += row[r];
                acc.block( subtotal );   // provide subtotal; block for completion
        }
    public:
        Adder( int row[ ], int size, Accumulator & acc ) : size( size ), row( row ), acc( acc ) {}
};
int main() {
        enum { rows = 10, cols = 10 };
        int matrix[rows][cols];
        Accumulator acc( rows );   // barrier synchronizes each summation
        // read matrix
        {
                uArray( Adder, adders, rows );
                for ( unsigned int r = 0; r < rows; r += 1 )
                        adders[r]( matrix[r], cols, acc );
        } // wait adders
        cout << acc.total() << " " << acc.Gth() << endl;
}
```

- Why not have task delete itself after unblocking from **uBarrier::block()** and make program main the coordinator?

```
void block( int subtotal ) {
    total_ += subtotal; uBarrier::block();
    delete &uThisTask();
}
// program main
acc.block( 0 );
```

- Coroutine barrier can be reused many times, e.g., read in a new matrix in `Accumulator::main` after each summation.
- Why can a barrier not be used within a `COFOR`? (any implicit concurrency)

6.3.4 Binary Semaphore

- **Binary semaphore** (Edsger W. Dijkstra) is blocking equivalent to yielding spin-lock.
- Provides synchronization *and* mutual exclusion.

```
Semaphore lock(0);    // 0 => closed, 1 => open, default 1
```

- More powerful than synchronization lock as it remembers state about an event.
- Names for acquire and release from Dutch terms
- acquire is `P`
  - passeren ⇒ to pass
  - prolagen ⇒ (proberen) to try (verlagen) to decrease

```
lock.P();             // wait to enter
```

  `P` waits if the semaphore counter is zero and then decrements it.

- release is `V`
  - vrijgeven ⇒ to release
  - verhogen ⇒ to increase

```
lock.V();             // release lock
```

  `V` increases the counter and unblocks a waiting task (if present).

- When the semaphore has only two states (open/closed), it is called a **binary semaphore**.
- synchronization

```
_Task T1 {                              | _Task T2 {
    BinSem & lk;                        |     BinSem & lk;
    void main() {                       |     void main() {
        . . .                           |         . . .
        S1                              |         lk.P();
        lk.V();                         |         S2
        . . .                           |         . . .
    }                                   |     }
  public:                               |   public:
    T1( BinSem & lk ) : lk(lk) {}       |     T2( BinSem & lk ) : lk(lk) {}
};                                      | };
```

```
int main() {
    BinSem lock( 0 ); // closed
    T1 t1( lock );
    T2 t2( lock );
}
```

- mutual exclusion

```
_Task T {
    BinSem & lk;
    void main() {
        . . .
        lk.P();
        // critical section
        lk.V();
        . . .
        lk.P();
        // critical section
        lk.V();
        . . .
    }
  public:
    T( BinSem & lk ) : lk(lk) {}
};
```

```
int main() {
    BinSem lock( 1 ); // start open
    T t0( lock ), t1( lock );
}
```

6.3.4.1 Implementation

- Implementation has:
  - blocking task-list
  - avail indicates if event has occurred (state)
  - spin lock to protect state

```
class BinSem {
    queue<Task> blocked;         // blocked tasks
    bool avail;                  // resource available ?
    SpinLock lock;               // mutex nonblocking lock
  public:
    BinSem( bool start = true ) : avail( start ) {}
    void P() {
        lock.acquire();          // prevention barging
        if ( ! avail ) {
            // add self to lock's blocked list
            yieldNoSchedule( lock );
            // DO NOT REACQUIRE LOCK
        }
        avail = false;
        lock.release();
    }
```

```
		void V() {
			lock.acquire();
			if ( ! blocked.empty() ) {
				// remove task from blocked list and make ready
				// DO NOT RELEASE LOCK
			} else {
				avail = true;		// conditional reset
				lock.release();		// NO RACE
			}
		}
	};
```

- Same as single-acquisition `mutexLock` but can initialize `avail`.

- Higher cost for synchronization if external lock already acquired.
  - ○ Might need `S.P( M )` to atomically block and release the mutual exclusion semaphore `M`.

6.3.5 Counting Semaphore

- Augment the definition of `P` and `V` to allow a multi-valued semaphore.

- What does it mean for a lock to have more than open/closed (unlocked/locked)?
  - ○ ⇒ critical sections allowing *N* simultaneous tasks.

- Augment `V` to allow increasing the counter an arbitrary amount.

- synchronization
  - ○ Three tasks must execute so S2 and S3 only execute after S1 has completed.

```
T1::main() {      T2::main() {      T3::main() {
    . . .             . . .             S1
    lk.P();           lk.P();           lk.V(); // lk.V(2)
    S2                S3                lk.V();
    . . .             . . .             . . .
}                 }                 }
int main() {
    CntSem lk( 0 ); // closed
    T1 x( lk );
    T2 y( lk );
    T3 z( lk );
}
```

- mutual exclusion
  - ○ Critical section allowing up to 3 simultaneous tasks.

```
_Task T {
    CntSem & lk;
    void main() {
        . . .
        lk.P();
        // up to 3 tasks in
        // critical section
        lk.V();
        . . .
    }
  public:
    T( CntSem & lk ) : lk(lk) {}
};
```

```
int main() {
    CntSem lk( 3 ); // allow 3
    T t0( lk ), t1( lk ), . . .;
}
```

- Must know in advance the total number of P's on the semaphore.

6.3.5.1 Implementation

- Change availability into counter, and set to some maximum on creation.
- Decrement counter on acquire and increment on release.
- Block acquiring task when counter is 0.
- Negative counter indicates number of waiting tasks.

```
class CntSem {
    queue<Task> blocked;    // blocked tasks
    int cnt;                // resource being used ?
    SpinLock lock;          // nonblocking lock
  public:
    CntSem( int start = 1 ) : cnt( start ) {}
    void P() {
        lock.acquire();
        cnt −= 1;
        if ( cnt < 0 ) {
            // add self to lock′s blocked list
            yieldNoSchedule( lock );
            // DO NOT REACQUIRE LOCK
        }
        lock.release();
    }
    void V() {
        lock.acquire();
        cnt += 1;
        if ( cnt <= 0 ) {
            // remove task from blocked list and make ready
            // DO NOT RELEASE LOCK
        } else {
            lock.release();     // NO RACE
        }
    }
};
```

- In general, binary/counting semaphores are used in two distinct ways:

1. For synchronization, if the semaphore starts at 0 ⇒ waiting for an event to occur.
2. For mutual exclusion, if the semaphore starts at 1(N) ⇒ controls a critical section.

- *µ*C++ provides a counting semaphore, `uSemaphore`, which subsumes a binary semaphore.

```
#include <uSemaphore.h>
class uSemaphore {
  public:
     uSemaphore( unsigned int count = 1 );
     void P();
     bool TryP();
     void V( unsigned int times = 1 );
     int counter() const;
     bool empty() const;
};
```

- `P` decrements the semaphore counter; if the counter is greater than or equal to zero, the calling task continues, otherwise it blocks.
- `TryP` returns **true** if the semaphore is acquired and **false** otherwise (never blocks).
- `V` wakes up the task blocked for the longest time if there are tasks blocked on the semaphore and increments the semaphore counter.
- If `V` is passed a positive integer N, the semaphore is `V`ed N times.
- The member routine `counter` returns the value of the semaphore counter:
  - ◦ negative means abs(N) tasks are blocked waiting to acquire the semaphore, and the semaphore is locked;
  - ◦ zero means no tasks are waiting to acquire the semaphore, and the semaphore is locked;
  - ◦ positive means the semaphore is unlocked and allows N tasks to acquire the semaphore.
- The member routine `empty` returns **false** if there are threads blocked on the semaphore and **true** otherwise.

6.4 Lock Programming

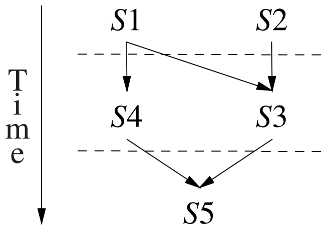
6.4.1 Precedence Graph

- Binary `P` and `V` in with `COBEGIN` are as powerful as `START` and `WAIT`.
- E.g., execute statements so the result is the same as serial execution but concurrency is maximized.

```
S1: a := 1
S2: b := 2
S3: c := a + b
S4: d := 2 * a
S5: e := c + d
```

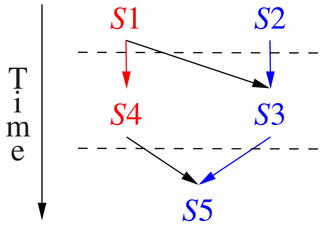
- Analyse which data and code depend on each other.
- i.e., statement `S1` and `S2` are independent ⇒ can execute in either order or at the same time.
- Statement `S3` is dependent on `S1` and `S2` because it uses both results.

- Display dependencies graphically in a **precedence graph** (different from process graph).



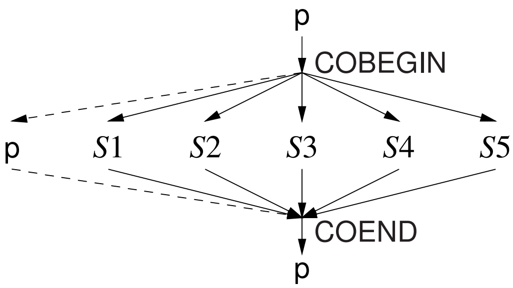
```
Semaphore L1(0), L2(0), L3(0), L4(0);
COBEGIN
    BEGIN a := 1; V(L1); END;
    BEGIN b := 2; V(L2); END;
    BEGIN P(L1); P(L2); c := a + b; V(L3); END;
    BEGIN P(L1); d := 2 * a; V(L4); END;
    BEGIN P(L3); P(L4); e := c + d; END;
COEND
```

- Does this solution work?
- Optimal solution: minimum threads, M, and traverse M paths through precedence graph.



```
Semaphore L1(0), L2(0);
COBEGIN
    BEGIN a := 1; V(L1); d := 2 * a; V(L2); END;
    BEGIN b := 2; P(L1); c := a + b; P(L2); e := c + d; END;
COEND
```

- process graph (different from precedence graph)

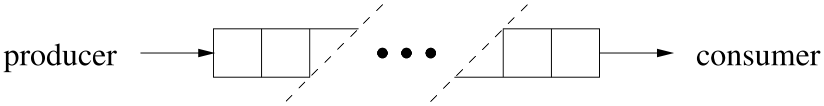


6.4.2 Buffering

- Tasks communicate unidirectionally through a queue.
- Producer adds items to the back of a queue.
- Consumer removes items from the front of a queue.

6.4.2.1 Unbounded Buffer

- Two tasks communicate through a queue of unbounded length.



- Because tasks work at different speeds, producer may get ahead of consumer.
  - Producer never has to wait as buffer has infinite length.
  - Consumer has to wait if buffer is empty ⇒ wait for producer to add.
- Queue is shared between producer/consumer, and counting semaphore controls access.

```
#define QueueSize ∞
int front = 0, back = 0;
int Elements[QueueSize];
uSemaphore full(0);
void Producer::main() {
    for (;;) {
        // produce an item
        // add to back of queue
        full.V();
    }
    // produce a stopping value
    full.V();
}
void Consumer::main() {
    for (;;) {
        full.P();
        // take an item from the front of the queue
      if ( stopping value ? ) break;
        // process or consume the item
    }
}
```

- Is there a problem adding and removing items from the shared queue?
- Is the full semaphore used for mutual exclusion or synchronization?

6.4.2.2 Bounded Buffer

- Two tasks communicate through a queue of bounded length.
- Because of bounded length:
  - Producer has to wait if buffer is full ⇒ wait for consumer to remove.
  - Consumer has to wait if buffer is empty ⇒ wait for producer to add.
- Use counting semaphores to account for the finite length of the shared queue.

```
uSemaphore full(0), empty(QueueSize);
void Producer::main() {
    for ( ;; ) {
        // produce an item
        empty.P();
        // add element to buffer
        full.V();
    }
    // produce a stopping value
    full.V();
}
void Consumer::main() {
    for ( ;; ) {
        full.P();
        // remove element from buffer
      if ( stopping value ? ) break;
        // process or consume the item
        empty.V();
    }
}
```

- Does this produce maximum concurrency?
- Can it handle multiple producers/consumers?

34	13	9	10	-3

full	empty
~~0~~	~~5~~
~~1~~	~~4~~
~~2~~	~~3~~
~~3~~	~~2~~
~~4~~	~~1~~
5	0

6.4.3 Lock Techniques

- Many possible solutions; need systematic approach.
- A **split binary semaphore** is a collection of semaphores where at most one of the collection has the value 1.
    - I.e., the sum of the semaphores is always less than or equal to one.
    - Used when different kinds of tasks have to block separately.
    - Cannot differentiate tasks blocked on the same semaphore (condition) lock. Why?
    - E.g., A and B tasks block on different semaphores so they can be unblocked based on kind, but collectively manage 2 semaphores like it was one.

- Split binary semaphores can be used to solve complicated mutual-exclusion problems by a technique called **baton passing**.
- The rules of baton passing are:
  - ○ there is exactly one (conceptual) baton
  - ○ nobody moves in the entry/exit code unless they have it
  - ○ once the baton is released, cannot read/write variables in entry/exit
- E.g., baton is conceptually acquired in entry/exit protocol and passed from signaller to signalled task (see page 98).

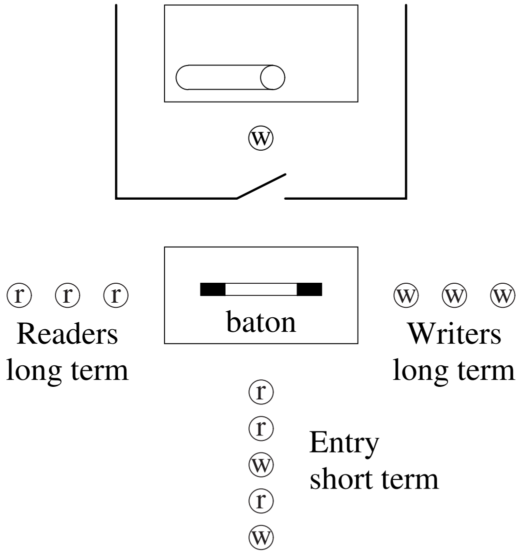
```
class BinSem {
        queue<Task> blocked;
        bool avail;
        SpinLock lock;
    public:
        BinSem( bool start = true ) : avail( start ) {}
        void P() {
                lock.acquire(); PICKUP BATON, CAN ACCESS STATE
                if ( ! avail ) {
                        // add self to lock's blocked list
                        PUT DOWN BATON, CANNOT ACCESS STATE
                        yieldNoSchedule( lock );
                        // UNBLOCK WITH SPIN LOCK ACQUIRED
                        PASSED BATON, CAN ACCESS STATE
                }
                avail = false;
                lock.release(); PUT DOWN BATON, CANNOT ACCESS STATE
        }
        void V() {
                lock.acquire(); PICKUP BATON, CAN ACCESS STATE
                if ( ! blocked.empty() ) {
                        // remove task from blocked list and make ready
                        PASS BATON, CANNOT ACCESS STATE
                } else {
                        avail = true;
                        lock.release(); PUT DOWN BATON, CANNOT ACCESS STATE
                }
        }
};
```

- Can mutex/condition lock perform baton passing to prevent barging?
  - ○ Not if signalled task must implicitly re-acquire the mutex lock before continuing.
  - ○ ⇒ signaller must release the mutex lock.
  - ○ There is now a race between signalled and calling tasks, resulting in barging.

6.4.4 Readers and Writer Problem

- Multiple tasks sharing a resource: some reading the resource and some writing the resource.
- Allow multiple concurrent reader tasks simultaneous access, but serialize access for writer tasks (a writer may read).

- Use split-binary semaphore to segregate 3 kinds of tasks: arrivers, readers, writers.
- Use baton-passing to help understand complexity.



6.4.4.1 Solution 1

```
uSemaphore entry(1), rwait(0), wwait(0); // split binary semaphores
int rdel = 0, wdel = 0, rcnt = 0, wcnt = 0; // auxiliary counters
void Reader::main() {
    entry.P();                          // pickup baton
    if ( wcnt > 0 ) {                   // occupied ?
        rdel += 1; entry.V();           // put baton down
        rwait.P(); rdel −= 1;           // passed baton
    }
    rcnt += 1;
    if ( rdel > 0 ) {                   // waiting readers ?
        rwait.V();                      // pass baton
    } else {
        entry.V();                      // put baton down
    }
    // READ
    entry.P();                          // pickup baton
    rcnt −= 1;
    if ( rcnt == 0 && wdel > 0 ) {      // waiting writers ?
        wwait.V();                      // pass baton
    } else {
        entry.V();                      // put baton down
    }
}
```

```
void Writer::main() {
        entry.P();                          // pickup baton
        if ( rcnt > 0 || wcnt > 0 ) {       // occupied ?
                wdel += 1; entry.V();       // put baton down
                wwait.P(); wdel -= 1;       // passed baton
        }
        wcnt += 1;
        entry.V();                          // put baton down
        // WRITE
        entry.P();                          // pickup baton
        wcnt -= 1;
        if ( rdel > 0 ) {                   // waiting readers ?
                rwait.V();                  // pass baton
        } else if ( wdel > 0 ) {            // waiting writers ?
                wwait.V();                  // pass baton
        } else {
                entry.V();                  // put baton down
        }
}
```

- Problem: reader only checks for writer in resource, never writers waiting to use it.
  - ⇒ readers barge ahead of writers who already waited.
  - ⇒ continuous stream of readers (actually only 2 needed) prevent waiting writers from making progress (starvation).

6.4.4.2 Solution 2

- Give writers priority and make the readers wait.
  - Works most of the time because normally 80% readers and 20% writers.
- Change entry protocol for reader to the following:

```
entry.P();                                  // pickup baton
if ( wcnt > 0 || wdel > 0 ) {               // waiting writers?
        rdel += 1; entry.V();               // put baton down
        rwait.P(); rdel -= 1;               // passed baton
}
rcnt += 1;
if ( rdel > 0 ) {                           // waiting readers ?
        rwait.V();                          // pass baton
} else {
        entry.V();                          // put baton down
}
```

- Also, change writer's exit protocol to favour writers:

```
entry.P();                        // pickup baton
wcnt -= 1;
if ( wdel > 0 ) {                 // check writers first
    wwait.V();                    // pass baton
} else if ( rdel > 0 ) {
    rwait.V();                    // pass baton
} else {
    entry.V();                    // put baton down
}
```

- ○ ⇒ writers barge.
- ○ ⇒ continuous stream of writers cause reader starvation.

6.4.4.3 Solution 3

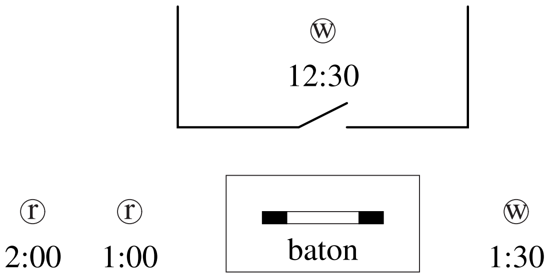
- Fairness on simultaneous arrival is solved by alternation (Dekker's solution).
- E.g., use `last` flag to indicate the kind of tasks last using the resource, i.e., reader or writer.
- On exit, first select from opposite kind, e.g., if `last` is reader, first check for waiting writer otherwise waiting reader, then update `last`.
- Flag is unnecessary if readers wait when there is a waiting writer, and all readers started after a writer.
- ⇒ put writer's exit-protocol back to favour readers.

```
entry.P();                        // pickup baton
wcnt -= 1;
if ( rdel > 0 ) {                 // check readers first
    rwait.V();                    // pass baton
} else if ( wdel > 0 ) {
    wwait.V();                    // pass baton
} else {
    entry.V();                    // put baton down
}
```

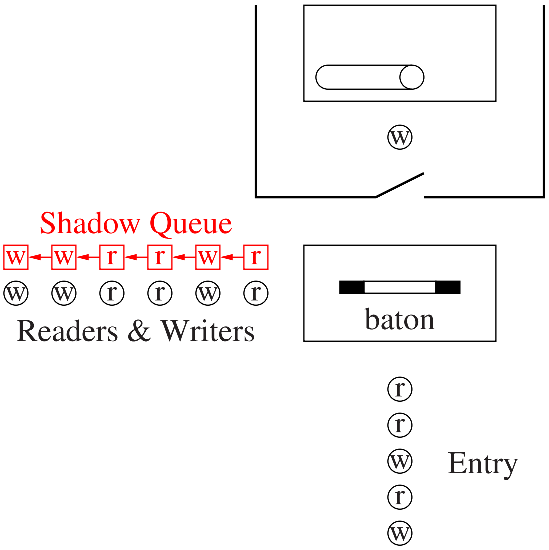
- **Arriving** readers cannot barge ahead of waiting writers and **unblocking** writers cannot barge ahead of a waiting reader
- ⇒ alternation for simultaneous waiting.

6.4.4.4 Solution 4

- Problem: temporal barging!
- Staleness/freshness for `last` flag and staleness with no-flag.



- Alternation for simultaneous waiting means when writer leaves resource:
  - both readers enter ⇒ 2:00 reader reads data that is **stale**; should read 1:30 write
  - writer enters and overwrites 12:30 data (never seen) ⇒ 1:00 reader reads data that is too **fresh** (i.e., missed reading 12:30 data)
- Staleness/freshness can lead to plane or stock-market crash.
- Service readers and writers in **temporal order**, i.e., first-in first-out (FIFO), but allow multiple concurrent readers.
- Have readers and writers wait on same semaphore ⇒ collapse split binary semaphore.
- ***But now lose kind of waiting task!***
- Introduce shadow queue to retain kind of waiting task on semaphore:



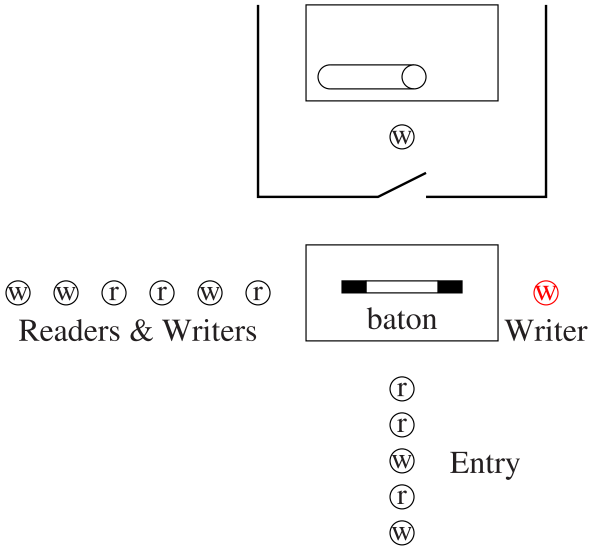
```
uSemaphore entry(1), rwwait(0);         // readers/writers, temporal order
int rwdel = 0, rcnt = 0, wcnt = 0;      // auxiliary counters
enum RW { READER, WRITER };             // kinds of tasks
queue<RW> rw_id;                        // queue of kinds
void Reader::main() {
    entry.P();                          // pickup baton
    if ( wcnt > 0 || rwdel > 0 ) {      // anybody waiting?
        rw_id.push( READER );           // store kind
        rwdel += 1; entry.V(); rwwait.P(); rwdel -= 1;
        rw_id.pop();
    }
    rcnt += 1;
    if ( rwdel > 0 && rw_id.front() == READER ) { // more readers ?
        rwwait.V();                     // pass baton
    } else
        entry.V();                      // put baton down
    // READ
    entry.P();                          // exit protocol
    rcnt -= 1;
    if ( rcnt == 0 && rwdel > 0 ) {     // last reader ?
        rwwait.V();                     // pass baton
    } else
        entry.V();                      // put baton down
}
void Writer::main() {
    entry.P();                          // pickup baton
    if ( rcnt > 0 || wcnt > 0 ) {
        rw_id.push( WRITER );           // store kind
        rwdel += 1; entry.V(); rwwait.P(); rwdel -= 1;
        rw_id.pop();
    }
    wcnt += 1;
    entry.V();                          // put baton down
    // WRITE
    entry.P();                          // pickup baton
    wcnt -= 1;
    if ( rwdel > 0 ) {                  // anyone waiting ?
        rwwait.V();                     // pass baton
    } else
        entry.V();                      // put baton down
}
```

- Why can task pop *front* node on shadow queue when unblocked?

6.4.4.5 Solution 5

- Cheat on cooperation:
  - allow 2 checks for write instead of 1
  - use reader/writer bench and writer chair.
- On exit, if chair empty, unconditionally unblock task at front of reader/writer semaphore.
- ⇒ ***reader can incorrectly unblock a writer.***

- This writer now waits second time but in chair.
- Chair is always checked first on exit (higher priority than bench).



```
uSemaphore entry(1), rwwait(0), wwait(0);
int rwdel = 0, wdel = 0, rcnt = 0, wcnt = 0; // auxiliary counters
void Reader::main() {
    entry.P();                          // pickup baton
    if ( wcnt > 0 || wdel > 0 || rwdel > 0 ) {
        rwdel += 1; entry.V(); rwwait.P(); rwdel -= 1;
    }
    rcnt += 1;
    if ( rwdel > 0 ) {                  // more readers ?
        rwwait.V();                     // pass baton
    } else
        entry.V();                      // put baton down
    // READ
    entry.P();                          // pickup baton
    rcnt -= 1;
    if ( rcnt == 0 ) {                  // last reader ?
        if ( wdel != 0 ) {              // writer waiting ?
            wwait.V();                  // pass baton
        } else if ( rwdel > 0 ) {       // anyone waiting ?
            rwwait.V();                 // pass baton
        } else
            entry.V();                  // put baton down
    } else
        entry.V();                      // put baton down
}
```

```
void Writer::main() {
    entry.P();                          // pickup baton
    if ( rcnt > 0 || wcnt > 0 ) {       // first wait ?
        rwdel += 1; entry.V(); rwwait.P(); rwdel -= 1;
        if ( rcnt > 0 ) {               // second wait ?
            wdel += 1; entry.V(); wwait.P(); wdel -= 1;
        }
    }
    wcnt += 1;
    entry.V();                          // put baton down
    // WRITE
    entry.P();                          // pickup baton
    wcnt -= 1;
    if ( rwdel > 0 ) {                  // anyone waiting ?
        rwwait.V();                     // pass baton
    } else
        entry.V();                      // put baton down
}
```

6.4.4.6 Solution 6

- Still temporal problem when tasks move from one blocking list to another.
- In solutions, reader/writer entry-protocols have code sequence:

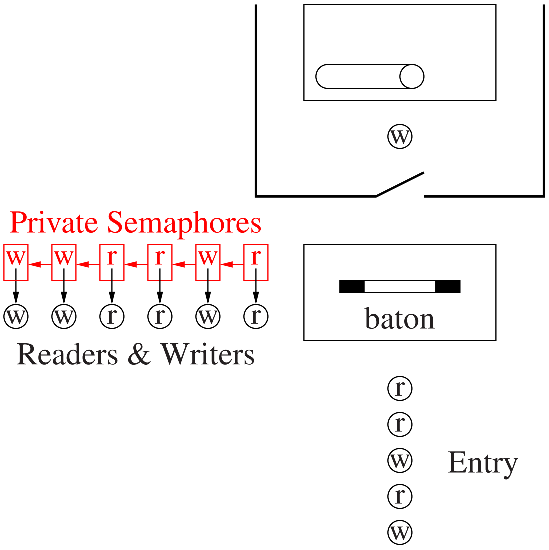
  ```
  . . . entry.V(); INTERRUPTED HERE Xwait.P();
  ```

- For writer:
  - pick up baton and see readers using resource
  - put baton down, `entry.V()`, but time-sliced before wait, `Xwait.P()`.
  - another writer does same thing, and this can occur to any depth.
  - writers restart in any order or immediately have another time-slice
  - e.g., 2:00 writer goes ahead of 1:00 writer ⇒ freshness problem.
- For reader:
  - pick up baton and see writer using resource
  - put baton down, `entry.V()`, but time-sliced before wait, `Xwait.P()`.
  - writers that arrived ahead of reader do same thing
  - reader restarts before any writers
  - e.g., 2:00 reader goes ahead of 1:00 writer ⇒ staleness problem.
- Need atomic block and release ⇒ magic like turning off time-slicing.

  ```
  Xwait.P( entry );       // uC++ semaphore
  ```

- Alternative: ticket
  - readers/writers take ticket (see Section 5.18.9, p. 87) before putting baton down
  - to pass baton, serving counter is incremented and then **WAKE ALL BLOCKED TASKS**
  - each task checks ticket with serving value, and one proceeds while others reblock
  - starvation not an issue as waiting queue is bounded length, but inefficient

- Alternative: private semaphore
  - list of **private semaphores**, one for each waiting task, versus multiple waiting tasks on a semaphore.
  - add list node before releasing entry lock, which establishes position, then block on private semaphore.
  - to pass baton, private semaphore at head of the queue is Ved, if present.
  - if task blocked on private semaphore, it is unblocked
  - if task not blocked due to time-slice, V is remembered, and task does not block on P.

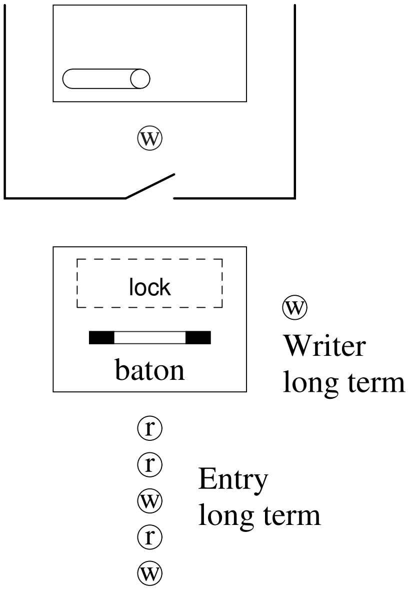


```
uSemaphore entry(1);
int rwdel = 0, rcnt = 0, wcnt = 0;
struct RWnode {
    RW rw;                              // kinds of task
    uSemaphore sem;                     // private semaphore
    RWnode( RW rw ) : rw(rw), sem(0) {}
};
queue<RWnode *> rw_id;
void Reader::main() {
    entry.P();                          // pickup baton
    if ( wcnt > 0 || ! rw_id.empty() ) { // anybody waiting?
        RWnode r( READER );
        rw_id.push( &r );               // store kind
        rwdel += 1; entry.V(); r.sem.P(); rwdel -= 1;
        rw_id.pop();
    }
    rcnt += 1;
    if ( rwdel > 0 && rw_id.front()->rw == READER ) { // more readers ?
        rw_id.front()->sem.V(); // pass baton
    } else
        entry.V();                      // put baton down
    // READ
```

```
        entry.P();                          // pickup baton
        rcnt -= 1;
        if ( rcnt == 0 && rwdel > 0 ) {     // last reader ?
            rw_id.front()->sem.V(); // pass baton
        } else
            entry.V();                      // put baton down
    }
    void Writer::main() {
        entry.P();                          // pickup baton
        if ( rcnt > 0 || wcnt > 0 ) {       // resource in use ?
            RWnode w( WRITER );
            rw_id.push( &w );               // remember kind of task
            rwdel += 1; entry.V(); w.sem.P(); rwdel -= 1;
            rw_id.pop();
        }
        wcnt += 1;
        entry.V();
        // WRITE
        entry.P();                          // pickup baton
        wcnt -= 1;
        if ( rwdel > 0 ) {                  // anyone waiting ?
            rw_id.front()->sem.V();         // pass baton
        } else
            entry.V();                      // put baton down
    }
```

6.4.4.7 Solution 7

- Ad hoc solution with questionable split-binary semaphores and baton-passing.



- Tasks wait in temporal order on entry semaphore.
- Only one writer ever waits on the writer chair until readers leave resource.
- *Waiting writer blocks holding baton to force other arriving tasks to wait on entry.*

- Semaphore `lock` is used only for mutual exclusion.
- Sometimes acquire two locks to prevent tasks entering and leaving.
- Release in opposite order.

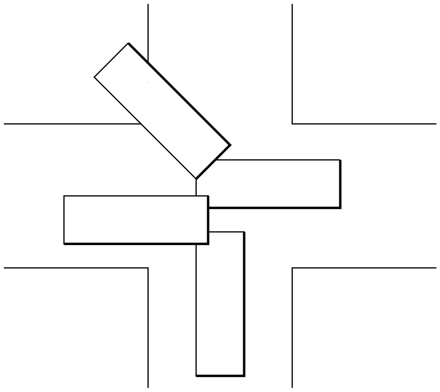
```
uSemaphore entry(1);                             // two locks open
uSemaphore lock(1), wwait(0);
int rcnt = 0, wdel = 0;

void Reader::main() {
    entry.P();                          // entry protocol
    lock.P();
    rcnt += 1;
    lock.V();
    entry.V();                          // put baton down
    // READ
    lock.P();                           // exit protocol
    rcnt -= 1;                          // critical section
    if ( rcnt == 0 && wdel == 1 ) {     // last reader & writer waiting ?
        lock.V();
        wwait.V();                      // pass baton
    } else
        lock.V();
}
void Writer::main() {
    entry.P();                          // entry protocol
    lock.P();
    if ( rcnt > 0 ) {                   // readers waiting ?
        wdel += 1;
        lock.V();
        wwait.P();                      // wait for readers
        wdel -= 1;                      // unblock with baton
    } else
        lock.V();
    // WRITE
    entry.V();                          // exit protocol
}
```

- Is temporal order preserved?
- While solution is smaller, harder to reason about correctness.
- Does not generalize for other kinds of complex synchronization and mutual exclusion.

7 Concurrent Errors

7.1 Race Condition

- A **race condition** occurs when there is missing synchronization and/or mutual exclusion.

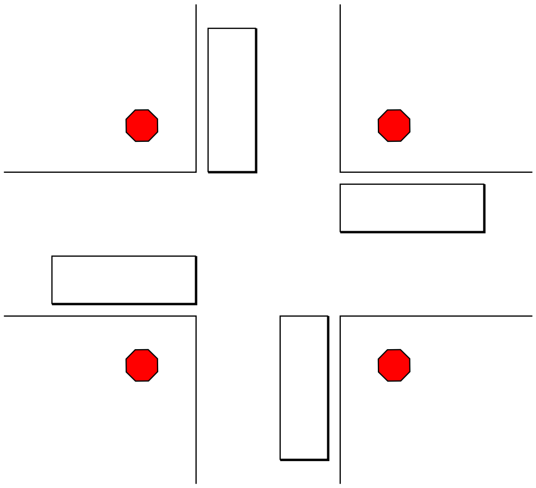


- Two or more tasks race along assuming synchronization or mutual exclusion has occurred.
- Can be very difficult to locate (thought experiments).
  - Aug. 14, 2003 Northeastern blackout : worst power outage in North American history.
  - Race condition buried in four million lines of C code.
  - "in excess of three million online operational hours in which nothing had ever exercised that bug."

7.2 No Progress

7.2.1 Live-lock

- Indefinite postponement: "You go first" problem on simultaneous arrival (symptom consuming CPU).

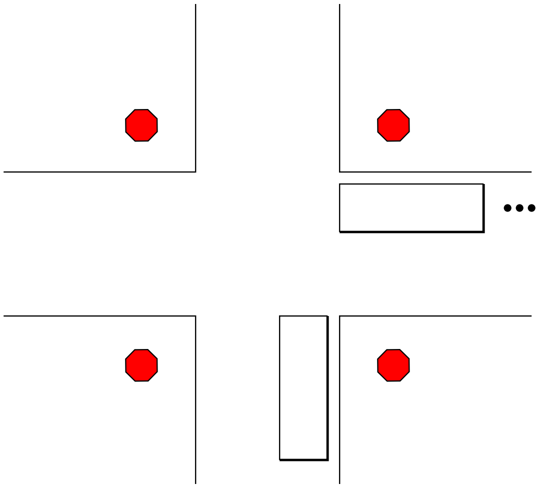


- Caused by poor scheduling in entry protocol. (Oracle with cardboard test)
- Always mechanism to break tie on simultaneous arrival to deal with live-lock.

7.2.2 Starvation

- A selection algorithm ignores one or more tasks so they are never executed, i.e., lack of long-term fairness (symptom consuming CPU).

- Long-term (infinite) starvation is rare, but short-term starvation can occur and is a problem.



- Like live-lock, starving task might be ready at any time, switching among active, ready and possibly blocked states.

7.2.3 Deadlock

- **Deadlock** is the state when one or more processes are waiting for an event that will not occur.

- Unlike live-lock/starvation, deadlocked task is (usually) blocked so not consuming CPU.

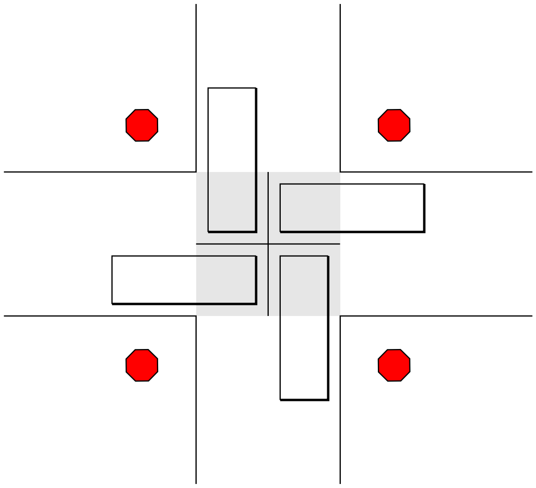
7.2.3.1 Synchronization Deadlock

- Failure in cooperation, so a blocked task is never unblocked (stuck waiting):

```
int main() {
    uSemaphore s(0);    // closed
    s.P();              // wait for lock to open
}
```

7.2.3.2 Mutual Exclusion Deadlock

- Failure to acquire a resource protected by mutual exclusion (need 2 critical sections).



- Deadlock, unless one of the cars is willing to backup (Oracle with cardboard test).
- There are 5 conditions that must occur for a set of processes to deadlock.
  1. A **concrete** shared-resource requiring mutual exclusion, i.e., exists without a task.
     - A task "wanting to drive across the intersection" is not a resource.
  2. A process holds a resource while waiting for access to a resource held by another process (hold and wait).
  3. Once a process has gained access to a resource, the runtime system cannot get it back (no preemption).
  4. There exists a circular wait of processes on resources.
  5. These conditions must occur simultaneously.
- Simple example using semaphores:

```
uSemaphore L1(1), L2(1);                          // open
     task1                   task2
L1.P()                  L2.P()                    // acquire opposite locks
     R1                      R2                   // access resource
     L2.P()                  L1.P()               // acquire opposite locks
          R1 & R2                 R2 & R1         // access resources
```

7.3 Deadlock Prevention

- Eliminate one or more of the conditions required for a deadlock from an algorithm ⇒ deadlock can never occur.

7.3.1 Synchronization Prevention

- Eliminate all synchronization from a program
- ⇒ no communication
- ⇒ impossible in most cases

7.3.2 Mutual Exclusion Prevention

- Deadlock can be prevented by eliminating one of the 5 conditions:

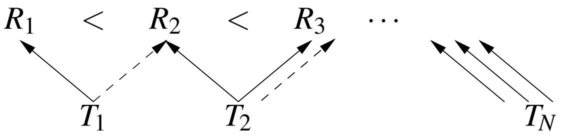
1. no mutual exclusion
    - ⇒ no shared resources
    - ⇒ impossible in most cases
2. no hold & wait: do not give any resource, unless all resources can be given

```
uSemaphore L1(1), L2(1);                    // open
     task1                  task2
L1.P() L2.P()          L1.P() L2.P()        // acquire all locks at start
     R1                     R2              // access resource
          R1 & R2                R2 & R1    // access resources
```

    - ⇒ poor resource utilization
    - possible starvation
3. allow preemption
    - Preemption is dynamic ⇒ cannot apply statically.
4. no circular wait: by controlling order of resource allocations

```
uSemaphore L1(1), L2(1);                    // open
     task1                  task2
L1.P()                 L1.P()               // acquire same locks
     R1                                     // access resource
     L2.P()                 L2.P()          // acquire same locks
                                 R2         // access resource
          R1 & R2                R2 & R1 // access resources
```

    - Use an **ordered resource** policy:



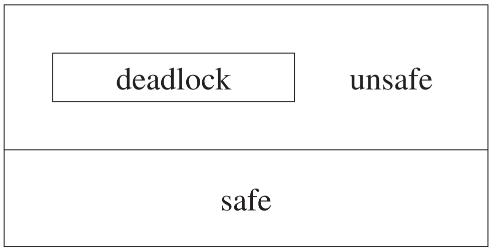
        - ○ divide all resources into classes R_1, R_2, R_3, etc.
        - ○ rule: can only request a resource from class R_i if holding no resources from any class R_j for $j \geq i$
        - ○ unless each class contains only one resource, requires requesting several resources simultaneously
        - ○ denote the highest class number for which T holds a resource by $h(T)$
        - ○ if process T_1 is requesting a resource of class k and is blocked because that resource is held by process T_2, then $h(T_1) < k \leq h(T_2)$
        - ○ as the preceding inequality is strict, a circular wait is impossible

  - ○ in some cases there is a natural division of resources into classes that makes this policy work nicely
  - ○ in other cases, some processes are forced to acquire resources in an unnatural sequence, complicating their code and producing poor resource utilization

5. prevent simultaneous occurrence:
   - Show previous 4 rules cannot occur simultaneously.

7.4 Deadlock Avoidance

- Monitor all lock blocking and resource allocation to detect any potential formation of deadlock.



- Achieve better resource utilization, but additional overhead to avoid deadlock.

7.4.1 Banker's Algorithm

- Demonstrate a safe sequence of resource allocations that ⇒ no deadlock.
- However, requires a process state its maximum resource needs.

	R1	R2	R3	R4	
	6	12	4	2	total resources (TR)
T1	4	10	1	1	maximum needed
T2	2	4	1	2	for execution
T3	5	9	0	1	(M)
T1	~~2~~3	5	1	0	currently
T2	1	2	1	0	allocated
T3	1	2	0	0	(C)

resource request (T1, R1) 2 → 3

T1	1	5	0	1	needed to get
T2	1	2	0	2	to maximum
T3	4	7	0	1	($N = M - C$)

current available resources

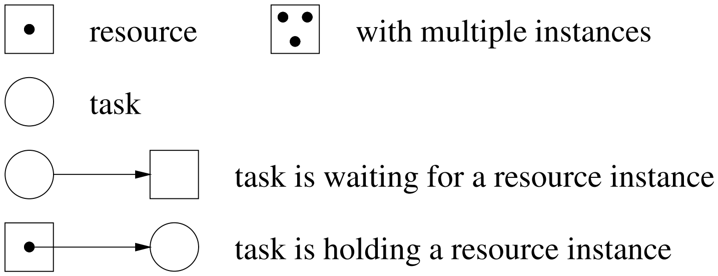
	1	3	2	2	($CR = TR - \sum C_{cols}$)
T2	0	1	2	0	($CR = CR - N_{T2}$)
	2	5	3	2	($CR = CR + M_{T2}$)
T1	1	0	3	1	($CR = CR - N_{T1}$)
	5	10	4	2	($CR = CR + M_{T1}$)
T3	1	3	4	1	($CR = CR - N_{T3}$)
	6	12	4	2	($CR = CR + M_{T3}$)

- Is there a safe order of execution that avoids deadlock should each process require its maximum resource allocation?
- A safe order exists (the left column in the table above) and hence the Banker's Algorithm allows the resource request.
- If there is a choice of processes to choose for execution, it does not matter which path is taken.

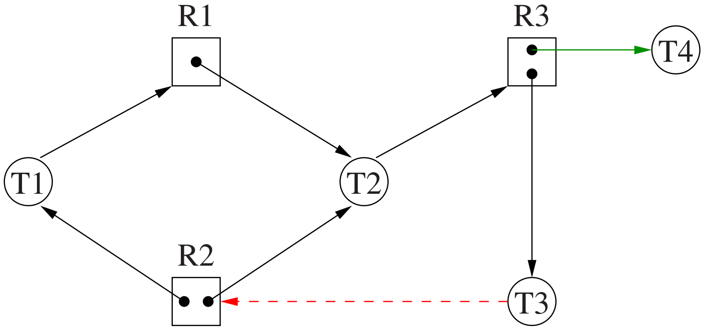
- Example: If T1 or T3 could go to their maximum with the current resources, then choose either. A safe order starting with T1 exists if and only if a safe order starting with T3 exists.
- Does task scheduling need to be adjusted to the safe sequence?
- The check for a safe order can be performed for every allocation of resource to a process (optimizations are possible, i.e., same thread asks for another resource).

7.4.2 Allocation Graphs

- One method to check for potential deadlock is to graph processes and resource usage at each moment a resource is allocated.



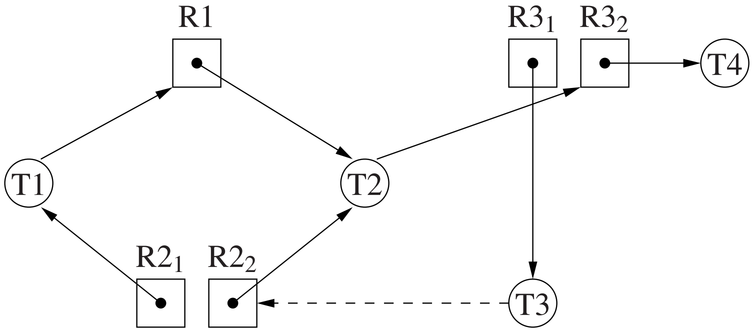
- Multiple instances are put into a resource so that a specific resource does not have to be requested. Instead, a generic request is made.



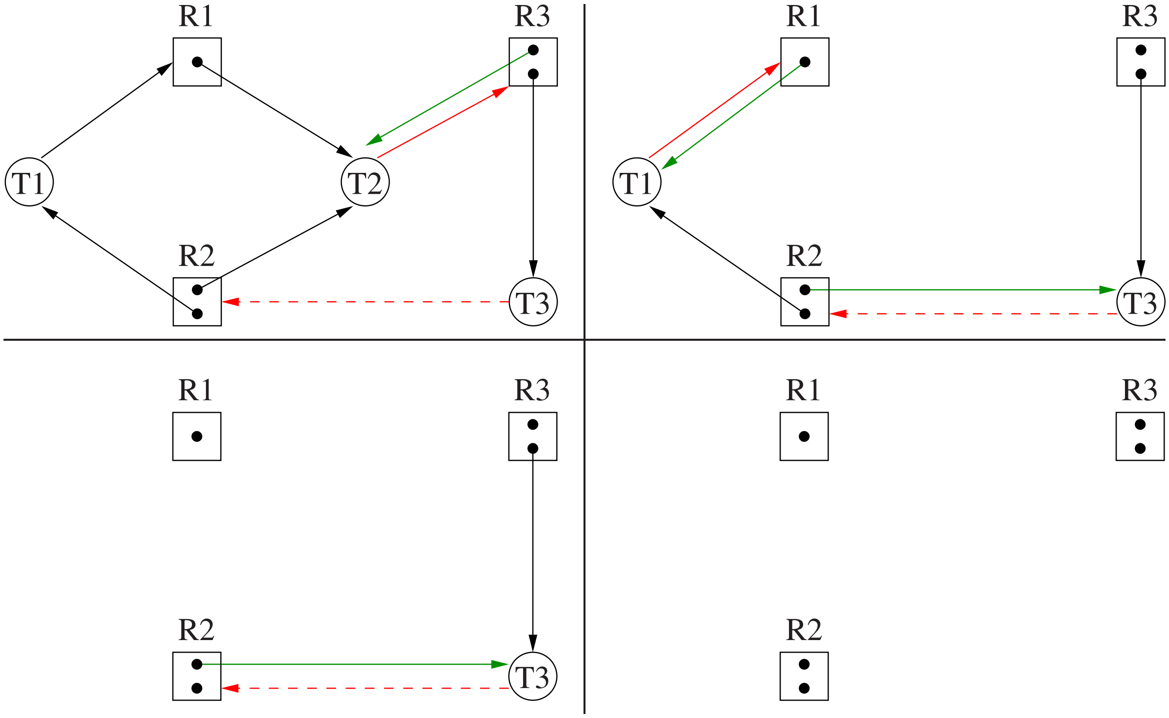
- If a graph contains no cycles, no process in the system is deadlocked.
- If any resource has several instances, a cycle $\not\Rightarrow$ deadlock.

  T1 → R1 → T2 → R3 → T3 → R2 → T1 (cycle)
  T2 → R3 → T3 → R2 → T2 (cycle)

  - If T4 releases its resource, the cycle is broken.
- Create **isomorphic graph** without multiple instances (expensive and difficult):



- If each resource has one instance, a cycle ⇒ deadlock.
- Use **graph reduction** to locate deadlocks:



- Problems:
  - When choices for tasks, selection is tricky (like isomorphic graph).
  - For large graphs, detecting cycles is expensive.
  - Many graphs to examine over time, one for each particular allocation state of the system.

7.5 Detection and Recovery

- Instead of avoiding deadlock let it happen and recover.
  - ⇒ ability to discover deadlock
  - ⇒ preemption
- Discovering deadlock is difficult, e.g., build and check for cycles in allocation graph.
  - not on each resource allocation, but every T seconds or every time a resource cannot be immediately allocated
  - **Try μC++ debugging macros to locate deadlock.**
- Recovery involves preemption of one or more processes in a cycle.
  - decision is not easy and must prevent starvation
  - The preemption victim must be restarted, from beginning or some previous checkpoint state, if you cannot guarantee all resources have not changed.
  - even that is not enough as the victim may have made changes before the preemption.

7.6 Which Method To Chose?

- Maybe “none of the above”: just ignore the problem
  - if some process is blocked for rather a long time, assume it is deadlocked and abort it
  - do this automatically in transaction-processing systems, manually elsewhere
- Of the techniques studied, only the ordered resource policy turns out to have much practical value.

8 Indirect Communication

- P and V are low level primitives for protecting critical sections and establishing synchronization between tasks.
- Shared variables provide the actual information that is communicated.
- Both of these can be complicated to use and may be incorrectly placed.
- Split-binary semaphores and baton passing are complex.
- Need higher level facilities that perform some of these details automatically.
- Get help from programming-language/compiler.

8.1 Critical Regions

- Declare which variables are to be shared, as in:

```
VAR v : SHARED INTEGER        MutexLock v_lock;
```

- Access to shared variables is restricted to within a REGION statement, and within the region, mutual exclusion is guaranteed.

```
REGION v DO                   v_lock.acquire()
    // critical section       . . .  // x = v; (read)  v = y (write)
END REGION                    v_lock.release()
```

- Simultaneous reads are impossible!
- Modify to allow reading of shared variables outside the critical region and modifications in the region.
- Problem: reading partially updated information while a task is updating the shared variable in the region.
- Nesting can result in deadlock.

```
VAR x, y : SHARED INTEGER

task1                 task2
REGION x DO              REGION y DO
    . . .                    . . .
    REGION y DO              REGION x DO
        . . .                    . . .
    END REGION               END REGION
    . . .                    . . .
END REGION               END REGION
```

8.2 Conditional Critical Regions

- Introduce a condition that must be true as well as having mutual exclusion.

```
REGION v DO
    AWAIT conditional-expression
    . . .
END REGION
```

- E.g., The consumer from the producer-consumer problem.

```
VAR Q : SHARED QUEUE<INT,10>

REGION Q DO
    AWAIT NOT EMPTY( Q ) buffer not empty
    take an item from the front of the queue
END REGION
```

- If the condition is false, the region lock is released and entry is started again (busy waiting).
- To prevent busy waiting, block on queue for shared variable, and on region exit, search for true conditional-expression and unblock.

8.3 Monitor

- A **monitor** is an abstract data type that combines shared data with serialization of its modification.

```
_Monitor name {
    shared data
    members that see and modify the data
};
```

- A **mutex member** (short for mutual-exclusion member) is one that does NOT begin execution if there is another active mutex member.
  - ⇒ a call to a mutex member may become blocked waiting entry, and queues of waiting tasks may form.
  - Public member routines of a monitor are implicitly mutex and other kinds of members can be made explicitly mutex with qualifier (**_Mutex**).
- Basically each monitor has a lock which is Ped on entry to a monitor member and Ved on exit.

```
class Mon {
    MutexLock mlock;
    int v;                      // shared data
  public:
    int x(. . .) {              // mutex member
        mlock.acquire();
        . . .          // int temp = v;
        mlock.release();
        return v;      // return temp;
    }
};
```

- Recursive entry is allowed (owner mutex lock), i.e., one mutex member can call another or itself.
- Unhandled exceptions raised within a monitor should always release the implicit monitor locks so the monitor can continue to function.
- Destructor must be mutex, so ending a block with a monitor or deleting a dynamically allocated monitor, blocks if thread in monitor.
- Atomic counter using a monitor:

```
_Monitor AtomicCounter {
        int counter;         // shared data
    public:
        AtomicCounter( int init = 0 ) : counter( init ) {}
        int inc() { counter += 1; return counter; }   // mutex members
        int dec() { counter -= 1; return counter; }
};
AtomicCounter a, b{ 1 }, c = { 3 };
. . . a.inc(); . . .          // accessed by multiple threads
. . . b.dec(); . . .
. . . c.inc(); . . .
```

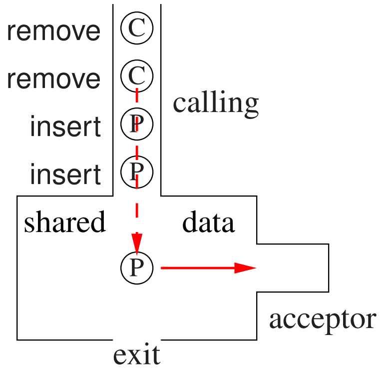
8.4 Scheduling (Synchronization)

- A monitor may want to schedule tasks in an order different from the order in which they arrive (bounded buffer, readers/write with staleness/freshness).
- There are two techniques: external and internal scheduling.
  - ◦ *external* is scheduling tasks outside the monitor and is accomplished with the accept statement.
  - ◦ *internal* is scheduling tasks inside the monitor and is accomplished using condition variables with signal and wait.

8.4.1 External Scheduling

- The accept statement controls which mutex members can accept calls.
- By preventing certain members from accepting calls at different times, it is possible to control scheduling of tasks.
- Each **_Accept** defines what cooperation must occur for the accepting task to proceed.
- E.g. Bounded Buffer

```
_Monitor BoundedBuffer {
        int front = 0, back = 0, count = 0;
        int elements[20];
    public:
        _Nomutex int query() const { return count; }
        [_Mutex] void insert( int elem );
        [_Mutex] int remove();
};
void BoundedBuffer::insert( int elem ) {
        if ( count == 20 ) _Accept( remove );
        elements[back] = elem;
        back = ( back + 1 ) % 20;
        count += 1;
}
int BoundedBuffer::remove() {
        if ( count == 0 ) _Accept( insert );
        int elem = elements[front];
        front = ( front + 1 ) % 20;
        count -= 1;
        return elem;
}
```



- Queues of tasks form outside the monitor, waiting to be accepted into either insert or remove.
- An acceptor blocks all calls except a call to the specified mutex member(s) occurs. (uses barging prevention)
- Accepted call is executed like a conventional member call.
- When the accepted task exits the mutex member (or waits), the acceptor continues.
- If the accepted task does an accept, it blocks, forming a stack of blocked acceptors.
- Alternative calls that satisfy accepter's requirement are possible:

  ```
  _Accept( insert || remove ); // one of insert or remove
  ```

- **_Nomutex** member ⇒ multiple threads in monitor ⇒ cannot be accepted.
- External scheduling is simple because unblocking (signalling) is implicit.

8.4.2 Internal Scheduling

- Scheduling among tasks inside the monitor.
- A **condition** is an external synchronization-lock (see Section 6.3.2, p. 101), i.e., queue of waiting tasks:

  ```
  uCondition x, y, z[5];
  ```

- empty returns **false** if there are tasks blocked on the queue and **true** otherwise.
- front returns an integer value stored with the waiting task at the front of the condition queue.
- A task waits (blocks) by placing itself on a condition:

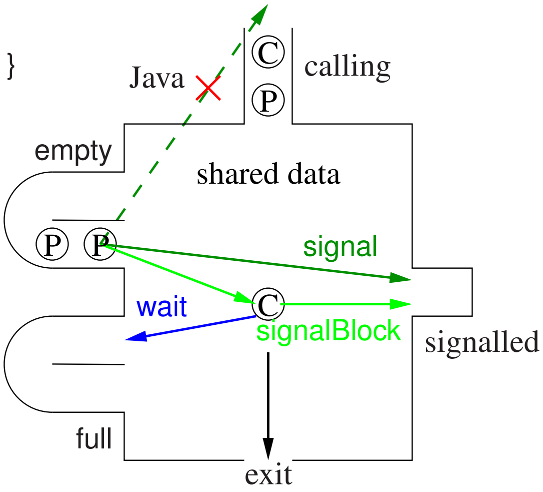
  ```
  x.wait();       // wait( mutex, condition )
  ```

  Atomically block at end of condition queue, and releasing the monitor lock so tasks can enter monitor. (uses barging avoidance)
- A task on a condition queue is made ready by signalling the condition:

  ```
  x.signal();
  ```

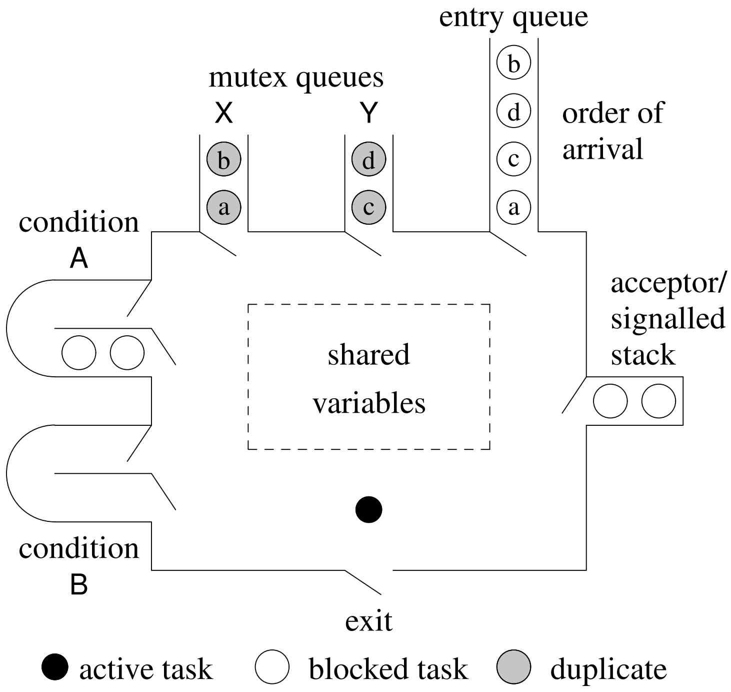
  Removes and makes ready blocked task at front of the condition queue.
- Signalled tasks scheduled before calling tasks ⇒ no barging, baton passing.
- **Signaller does not block, so the signalled task must continue waiting until the signaller exits or waits.**
- Like a SyncLock, a signal on an empty condition is lost!
- E.g. Bounded Buffer (like binary semaphore solution):

```
_Monitor BoundedBuffer {
    uCondition full, empty;
    int front = 0, back = 0, count = 0;
    int elements[20];
  public:
    _Nomutex int query() const { return count; }
    void insert( int elem ) {
        if ( count == 20 ) empty.wait();
        elements[back] = elem;
        back = ( back + 1 ) % 20;
        count += 1;
        full.signal();
    }
    int remove() {
        if ( count == 0 ) full.wait();
        int elem = elements[front];
        front = ( front + 1 ) % 20;
        count -= 1;
        empty.signal();
        return elem;
    }
};
```



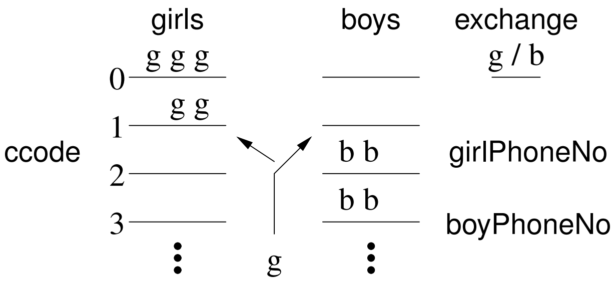
- **wait()** blocks current thread, and restarts a signalled task or implicitly releases monitor lock.
- **signal()** unblocks thread on the front of the condition queue *after* the signaller thread blocks or exits.
- **signalBlock()** unblocks thread on the front of the condition queue and blocks signaller thread.
- General Model

```
_Monitor Mon {
    uCondition A, B;
    . . .
  public:
    int X(. . .) {. . .}
    void Y(. . .) {. . .}
};
```



- **entry queue** is FIFO list of calling tasks to the monitor.

- When to use external or internal scheduling?
- External is easier to specify and explain over internal with condition variables.
- However, external scheduling cannot be used if:
  - scheduling depends on member parameter value(s), e.g., compatibility code for dating
  - scheduling must block in the monitor but cannot guarantee the next call fulfills cooperation
- Dating service



```
_Monitor DatingService {
    enum { CCodes = 20 };  // compatibility codes
    uCondition girls[CCodes], boys[CCodes], exchange;
    int girlPhoneNo, boyPhoneNo;
  public:
    int girl( int phoneNo, int ccode ) {
        if ( boys[ccode].empty() ) {         // no compatible boy ?
            girls[ccode].wait();             // wait for boy
            girlPhoneNo = phoneNo;           // make phone number available
            exchange.signal();               // wake boy from chair
        } else {
            girlPhoneNo = phoneNo;           // make phone number available
            // signalBlock() & remove exchange
            boys[ccode].signal();            // wake boy
            exchange.wait();                 // sit in chair
        }
        return boyPhoneNo;
    }
    int boy( int phoneNo, int ccode ) {
        // same as above, with boy/girl interchanged
    }
};
```

- Also, possible to use signal with empty bench (ccode) as chair.

8.5 Readers/Writer

- Solution 3 (Section 6.4.4.3, p. 120), no bargers, 5 rules, not temporal

```
_Monitor ReadersWriter {
        int rcnt = 0, wcnt = 0;
        uCondition readers, writers;
    public:
        void startRead() {
            if ( wcnt != 0 || ! writers.empty() ) readers.wait();
            rcnt += 1;
            readers.signal();
        }
        void endRead() {
            rcnt -= 1;
            if ( rcnt == 0 ) writers.signal();
        }
        void startWrite() {
            if ( wcnt !=0 || rcnt != 0 ) writers.wait();
            wcnt = 1;
        }
        void endWrite() {
            wcnt = 0;
            if ( ! readers.empty() ) readers.signal();
            else writers.signal();
        }
};
```

- Problem: has the same usage protocol as P and V.

```
ReadersWriter rw;
    readers                 writers
rw.startRead()          rw.startWrite()    // 2-step protocol
// read                 // write
rw.endRead()            rw.endWrite()
```

- Simplify protocol:

```
ReadersWriter rw;
    readers                 writers
rw.read(...)            rw.write(...)      // 1-step protocol
```

  - Implies only one read/write action, or pass pointer to read/write action.

- Alternative interface:

```
_Monitor ReadersWriter {
        _Mutex void startRead() { ... }
        _Mutex void endRead() { ... }
        _Mutex void startWrite() { ... }
        _Mutex void endWrite() { ... }
    public:
        _Nomutex void read(...) { // no const or mutable
            startRead();     // acquire mutual exclusion
            // read, no mutual exclusion
            endRead();       // release mutual exclusion
        }
```

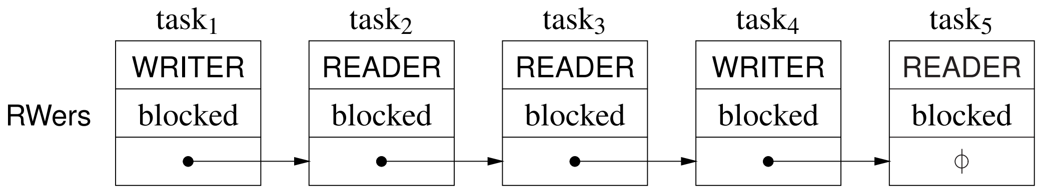
```
        _Nomutex void write(. . .) { // no const or mutable
            startWrite()       // acquire mutual exclusion
            // write
            endWrite()         // release mutual exclusion
        }
    };
```

- Alternative interface, and remove wcnt (barging prevention):

```
    _Monitor ReadersWriter {
        _Mutex void startRead() {
            if ( ! writers.empty() ) readers.wait();
            rcnt += 1;
            readers.signal();
        }
        _Mutex void endRead() { . . . }
      public:
        _Nomutex void read(. . .) { // no const or mutable
            startRead();       // acquire mutual exclusion
            // read, no mutual exclusion
            endRead();         // release mutual exclusion
        }
        void write(. . .) {        // acquire mutual exclusion
            if ( rcnt != 0 ) writers.wait(); // release/reacquire
            // write, mutual exclusion
            if ( ! readers.empty() ) readers.signal();
            else writers.signal();
        }
    };
```

- Solution 4 (Section 6.4.4.4, p. 120), condition shadow queue with type uintptr_t data.

```
    _Monitor ReadersWriter {
        int rcnt = 0, wcnt = 0;
        uCondition RWers;
        enum RW { READER, WRITER };
      public:
        void startRead() {
            if ( wcnt !=0 || ! RWers.empty() ) RWers.wait( READER );
            rcnt += 1;
            if ( ! RWers.empty() && RWers.front() == READER ) RWers.signal();
        }
        void endRead() {
            rcnt −= 1;
            if ( rcnt == 0 ) RWers.signal();
        }
        void startWrite() {
            if ( wcnt != 0 || rcnt != 0 ) RWers.wait( WRITER );
            wcnt = 1;
        }
        void endWrite() {
            wcnt = 0;
            RWers.signal();
        }
    };
```



- Use shadow queue to solve dating service, i.e., shadow with phone number.
- μC++ uCondLock and uSemaphore also support shadow queues with type uintptr_t data.
- Solution 8, external scheduling

```
_Monitor ReadersWriter {
    int rcnt = 0, wcnt = 0;
  public:
    void endRead() {
        rcnt -= 1;
    }
    void endWrite() {
        wcnt = 0;
    }
    void startRead() {
        if ( wcnt > 0 ) _Accept( endWrite );
        rcnt += 1;
    }
    void startWrite() {
        if ( wcnt > 0 ) _Accept( endWrite );
        else while ( rcnt > 0 ) _Accept( endRead );
        wcnt = 1;
    }
};
```

- Why has the order of the member routines changed?

8.6 Exceptions

- An exception raised in a monitor member propagates to the caller's thread.

```
_Monitor M {
  public:
    void mem1() {
        ... if ( ... ) _Throw E(); ... // E goes to caller
    } // uRendezvousFailure goes to "this"
    void mem2() {
        try {
            ... if ( ... ) _Accept( mem1 ); ... // assume rendezvous completed
        } catch( uMutexFailure::RendezvousFailure & ) { // implicitly enabled
            // deal with rendezvous failure
        } // try
    }
};
```

- Caller in M::mem1 gets exception E propagated on its stack.

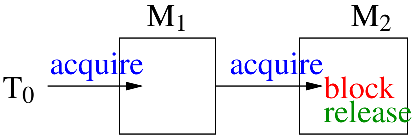
- On exiting M::mem1, caller implicitly raises non-local RendezvousFailure exception at monitor acceptor's thread to identify failed cooperation.
- RendezvousFailure always enabled ⇒ **_Enable** block unnecessary.
- For multiple **_Accept** clauses

  ```
  _Accept( mem2 || mem3 || ... );
  ```

  flag variable required to know which member failed.

8.7 Nested Monitor Calls

- **Nested monitor problem**: acquire monitor (lock) M_1, call to monitor M_2, and wait on condition in M_2.



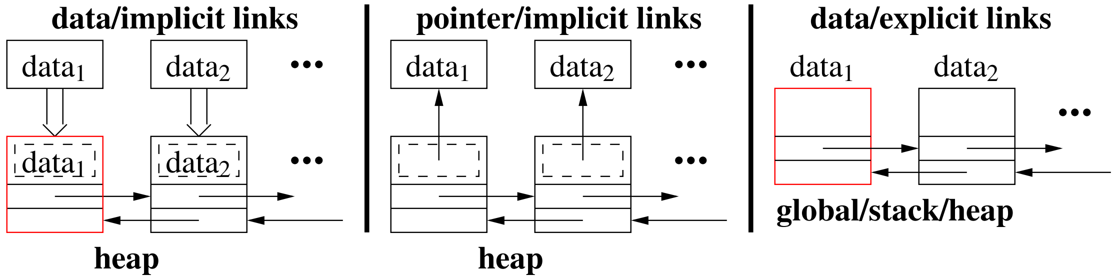
- Monitor M_2's mutex lock is released by wait, but monitor M_1's monitor lock is NOT released ⇒ potential deadlock.
- Releasing all locks can inadvertently release a lock, e.g., incorrectly release M_0 before M_1.
- Same problem occurs with locks.
- Called **lock composition** problem.
- Nested monitor used as guardian lock for readers/writer problem (like external scheduling RW page 145).

```
_Monitor RW {
    _Monitor RWN {
        uCondition bench;
        int rcnt = 0;
      public:
        void startRead() { rcnt += 1; }
        void endRead()  { rcnt -= 1;  if ( rcnt == 0 ) bench.signal(); }
        void startEndWrite() {
            if ( rcnt > 0 ) bench.wait();         // blocking holding rw
            // sequential write
        }
    } rwn;
    _Mutex void mutexRead() { rwn.startRead(); }
  public:
    void write() { rwn.startEndWrite(); }
    _Nomutex void read() {
        mutexRead();
        // concurrent reads
        rwn.endRead();                            // let readers out
    }
};
```

- If the writer waits in rwn, it prevent both readers and writers acquiring rw, which prevents starvation and forces FIFO ordering.

8.8 Intrusive Lists

- Non-contiguous variable-length data-structures, e.g., list, dictionary, normally require dynamic allocation as the structure increases/deceases when adding/deleting nodes.
- 3 kinds of collection node: data/implicit links, pointer/implicit links, and data/explicit links.



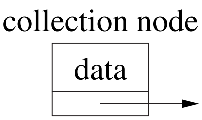
implicit data has no links ⇒ heap allocate node with links and data/pointer, copy data/pointer into node.

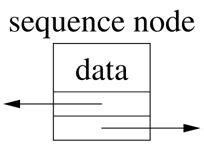
explicit data contains links (**intrusive**) ⇒ global/stack/heap allocate node, data may already exist in node.

- C++ collections (e.g., list) implicitly manage nodes ⇒ no lifetime issues for copied data.
- μC++ collections require programmer to manage nodes ⇒ lifetime issues.

```
struct Node : public uColable {
    int i;
    Node( int i ) : i{ i } {}
};
int main() {
    Node n1{ 1 }, n2{ 2 }, n3{ 3 };                  // stack nodes
    uStack<Node> s;
    s.push( &n1 );  s.push( &n2 );  s.push( &n3 );   // no dynamic allocation
    Node * sp;
    for ( uStackIter<Node> si(s); si >> sp; ) cout << sp->i << " ";
    cout << endl;
}
```

- μC++ intrusive lists have two formats: one link field (uColable) for a collection, and two link fields (uSeqable) for a sequence.





```
class stacknode : public uColable { ... }
class queuenode : public uColable { ... }
class seqnode : public uSeqable { ... }
```

- Template classes uStack/uQueue (singly linked) are collections and uSequence (doubly linked) is a sequence.
- uSeqable node appears in sequence/collection; uColable node appears only in a collection.

- Each kind of intrusive list has associated iterators: uStackIter, uQueueIter, uSeqIter.
- See μC++ reference manual Appendix C for details and examples.
- Concurrency pattern shows how threads use intrusive lists without dynamic allocation.

```
if ( . . . ) {
    Node n{ . . . }          // allocate on thread stack
    queue.add( n );          // chain stack node onto list
    // block
    queue.drop();            // node n must be at head/tail of list
} // automatically free n
```

- Lifetime of node is duration of blocked thread (see above pattern in shadow queue page 121 and private semaphore page 125).
- μC++ uses private, embedded intrusive-links for chaining *non-copyable* task objects on and off of waiting and ready queues.

8.9 Counting Semaphore, V, P vs. Condition, Signal, Wait

- There are several important differences between these mechanisms:
  - P only blocks if semaphore = 0, wait always blocks
  - V before P affects the P, while signal before wait is lost (no state)
  - multiple Vs may start multiple tasks simultaneously, while multiple signals only start one task at a time because each task must exit serially through the monitor
- Possible to simulate P and V using a monitor:

```
_Monitor semaphore {
    int sem;
    uCondition semcond;
  public:
    semaphore( int cnt = 1 ) : sem( cnt ) {}
    void P() {
        if ( sem == 0 ) semcond.wait();
        sem -= 1;
    }
    void V() {
        sem += 1;
        semcond.signal();
    }
};
```

- Can this simulation be reduced?

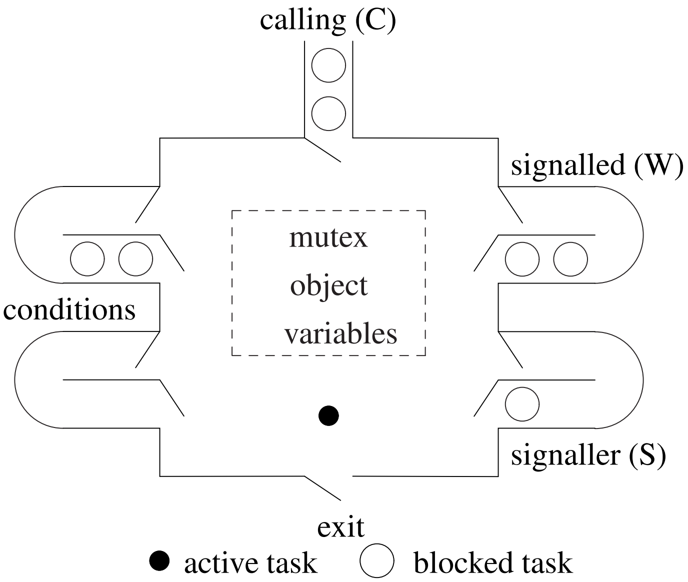
8.10 Monitor Types

- **explicit scheduling** occurs when:
  - An accept statement blocks the active task on the acceptor stack and makes a task ready from the specified mutex member queue.
  - A signal moves a task from the specified condition to the signalled stack.

- **implicit scheduling** occurs when a task waits in or exits from a mutex member, and a new task is selected first from the A/S stack, then the entry queue.
-

explicit scheduling	internal scheduling (signal)
	external scheduling (accept)
implicit scheduling	monitor selects (wait/exit)

- Monitors are classified by the implicit scheduling (who gets control) of the monitor when a task waits or signals or exits.
- Implicit scheduling can select from the calling (C), signalled (W), and signaller (S) queues.



  ○ Assigning different relative priorities to the queues creates different monitors.

	relative priority	
1	**C** < W < S	**Useful, has Prevention**
2	**C** < S < W	no barging
3	**C** = W < S	**Usable, needs Avoidance**
4	**C** = S < W	barging, starvation without avoidance
5	C = **W = S**	**Rejected**, **Confusing**
6	C < **W = S**	arbitrary selection
7	S = W < **C**	**Rejected, Unsound**
8	W < S = **C**	uncontrolled barging,
9	W < **C** < S	unpreventable starvation
10	S < W = **C**	
11	S < **C** < W	
12	W < S < **C**	
13	S < W < **C**	

- Implicit Signal
  - Monitors either have an explicit signal (statement) or an implicit signal (automatic signal).
  - The implicit signal monitor has no condition variables or explicit signal statement.
  - Instead, there is a waitUntil statement, e.g.:

    waitUntil *logical-expression*
  - The implicit signal causes a task to wait until the conditional expression is true.

```
_Monitor BoundedBuffer {
    int front = 0, back = 0, count = 0;
    int elements[20];
  public:
    _Nomutex int query() const { return count; }
    void insert( int elem ) {
        waitUntil count != 20; // not in uC++
        elements[back] = elem;
        back = ( back + 1 ) % 20;
        count += 1;
    }
    int remove() {
        waitUntil count != 0; // not in uC++
        int elem = elements[front];
        front = ( front + 1 ) % 20;
        count −= 1;
        return elem;
    }
};
```

- Additional restricted monitor-type requiring the signaller exit immediately from monitor (i.e., signal ⇒ return), called **immediate-return signal**.
  - not powerful enough to handle all cases, e.g., dating service, but optimizes the most common case of signal before return.
- Remaining monitor types:

signal type	priority	no priority
Blocking	Priority Blocking (Hoare) $C < S < W$ (μC++ signalBlock)	No Priority Blocking $C = S < W$
Nonblocking	Priority Nonblocking $C < W < S$ (μC++ signal)	No Priority Nonblocking $C = W < S$ (Java/C#)
Implicit Signal	Priority Implicit Signal $C < W$	No Priority Implicit Signal $C = W$

  - no-priority blocking requires the **signaller task** to recheck the waiting condition in case of a barging task.

    ⇒ use a **while** loop around a signal
  - no-priority non-blocking requires the **signalled task** to recheck the waiting condition in case of a barging task.

    ⇒ use a **while** loop around a wait

  - implicit (automatic) signal is good for **prototyping** but have poor performance.
  - priority nonblocking has no barging and optimizes signal before return (supply cooperation).
  - priority blocking has no barging and handles internal cooperation within the monitor (wait for cooperation).

- coroutine monitor (**_Cormonitor**)
  - coroutine with implicit mutual exclusion on calls to specified member routines:

```
_Mutex _Coroutine C {   // _Cormonitor
    void main() {
        . . . suspend() . . .
        . . . suspend() . . .
    }
  public:
    void m1( . . . ) { . . . resume(); . . . }    // mutual exclusion
    void m2( . . . ) { . . . resume(); . . . }    // mutual exclusion
    . . . // destructor is ALWAYS mutex
};
```

  - can use resume(), suspend(), condition variables (wait(), signal(), signalBlock()) or **_Accept** on mutex members.
  - coroutine can now be used by multiple threads, e.g., coroutine print-formatter accessed by multiple threads.

8.11 Java Monitor

- Java has **synchronized** class members (i.e., _Mutex members but **incorrectly named**), and a **synchronized** statement.
- All classes have **one** implicit condition variable and these routines to manipulate it:

```
public wait();
public notify();
public notifyAll()
```

  - Java concurrency library has multiple conditions but incompatible with language condition (see Section 11.6.1, p. 201).

- Internal scheduling is no-priority nonblocking ⇒ **barging**
  - wait statements must be in while loops to recheck conditions.

- Bounded buffer:

```
class Buffer {
    // buffer declarations
    private int count = 0;
    public synchronized void insert( int elem ) {
        while ( count == Size ) wait(); // busy-waiting
        // add to buffer
        count += 1;
        if ( count == 1 ) notifyAll();
    }
```

```
        public synchronized int remove() {
            while ( count == 0 ) wait();     // busy-waiting
            // remove from buffer
            count -= 1;
            if ( count == Size - 1 ) notifyAll();
            return elem;
        }
    }
```

- Only one condition queue, producers/consumers wait together ⇒ unblock all tasks.

- Only one condition queue ⇒ certain solutions are difficult or impossible.

- Erroneous Java implementation of barrier:

```
    class Barrier {                             // monitor
        private int N, count = 0;
        public Barrier( int N ) { this.N = N; }
        public synchronized void block() {
            count += 1;                         // count each arriving task
            if ( count < N )
                try { wait(); } catch( InterruptedException e ) {}
            else                                // barrier full
                notifyAll();                    // wake all barrier tasks
            count -= 1;                         // uncount each leaving task
        }
    }
```

  - ◦ Nth task does notifyAll, leaves monitor and performs its *i*th step, and then races back (barging) into the barrier before any notified task restarts.
  - ◦ It sees count still at N and incorrectly starts its *i*th+1 step before the current tasks have completed their *i*th step.

- Fix by modifying code for Nth task to set count to 0 (barging avoidance) and removing `count -= 1`.

```
        else {                          // barrier full
            count = 0;                  // reset count
            notifyAll();                // wake all barrier tasks
        }
```

- Technically, still wrong because of **spurious wakeup** ⇒ requires loop around wait.

```
        if ( count < N )
            while ( ??? )  // cannot be count < N as count is always < N
                try { wait(); } catch( InterruptedException e ) {}
```

- Requires more complex implementation.

```
class Barrier {                          // monitor
    private int N, count = 0, generation = 0;
    public Barrier( int N ) { this.N = N; }
    public synchronized void block() {
        int mygen = generation;
        count += 1;                      // count each arriving task
        if ( count < N )                 // barrier not full ? => wait
            while ( mygen == generation )
                try { wait(); } catch( InterruptedException e ) {}
        else {                           // barrier full
            count = 0;                   // reset count
            generation += 1;             // next group
            notifyAll();                 // wake all barrier tasks
        }
    }
}
```

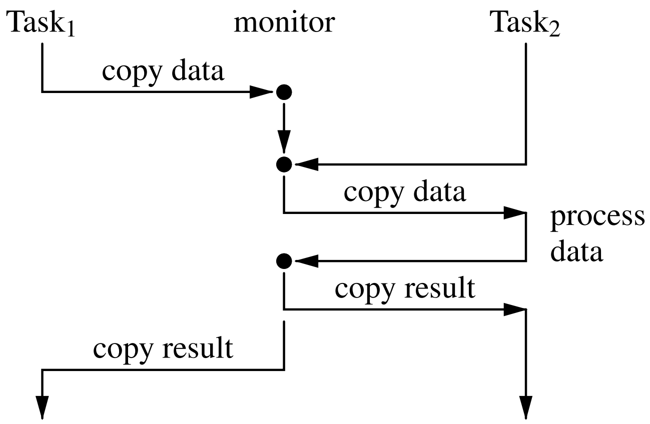
- Misconception of building condition variables in Java with nested monitors:

```
class Condition {                        // try to build condition variable
    public synchronized void Wait() {
         try { wait(); } catch( InterruptedException ex ) {};
    }
    public synchronized void Notify() { notify(); }
}
class BoundedBuffer {
    // buffer declarations
    private Condition full = new Condition(), empty = new Condition();
    public synchronized void insert( int elem ) {
        while ( count == NoOfElems ) empty.Wait(); // block producer
        // add to buffer
        count += 1;
        full.Notify();                   // unblock consumer
    }
    public synchronized int remove() {
        while ( count == 0 ) full.Wait(); // block consumer
        // remove from buffer
        count −= 1;
        empty.Notify();                  // unblock producer
        return elem;
    }
}
```

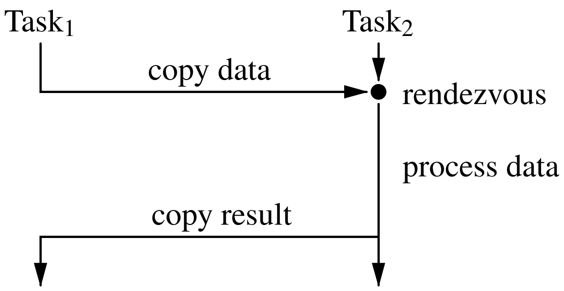
- Deadlocks at `empty.Wait()`/`full.Wait()` as buffer monitor-lock is not released.

9 Direct Communication

- Monitors work well for passive objects that require mutual exclusion because of sharing.
- However, communication among tasks with a monitor is indirect.
- Problem: point-to-point with reply indirect communication:



- Point-to-point with reply direct communication:



- Tasks can communicate directly by calling each others member routines.
- Member call is synchronous, nonlocal exception is asynchronous and indirect.

9.1 Task

- A task is like a coroutine because it has a distinguished member, (task main), which has its own execution state.
- A task is unique because it has a thread of control, which begins execution in the task `main` when the task is created.
- A task is like a monitor because it provides mutual exclusion (and synchronization) so only one thread is active in the object.
  - public members of a task are implicitly mutex and other kinds of members can be made explicitly mutex.
  - external scheduling allows direct calls to mutex members (task's thread blocks while caller's executes).

  - without external scheduling, tasks must *call out* to communicate ⇒ third party, or somehow emulate external scheduling with internal.

- In general, basic execution properties produce different abstractions:

object properties		member routine properties	
thread	stack	No S/ME	S/ME
No	No	**1** class	**2** monitor
No	Yes	**3** coroutine	**4** coroutine-monitor
Yes	No	**5** **reject**	**6** **reject**
Yes	Yes	**7** **reject?**	**8** task

- When thread or stack is missing it comes from calling object.
- Abstractions are not ad-hoc, rather derived from basic properties.
- Each of these abstractions has a particular set of problems it can solve, and therefore, each has a place in a programming language.

9.2 Scheduling

- A task may want to schedule access to itself by other tasks in an order different from the order in which requests arrive.
- As for monitors, there are two techniques: external and internal scheduling.

9.2.1 External Scheduling

- As for a monitor (see Section 8.4.1, p. 139), the accept statement can be used to control which mutex members of a task can accept calls.

```
_Task BoundedBuffer {
        int front = 0, back = 0, count = 0;
        int Elements[20];
    public:
        _Nomutex int query() const { return count; }
        void insert( int elem ) {
            if ( count == 20 ) _Accept( remove ); // move to main
            Elements[back] = elem;
            back = ( back + 1 ) % 20;
            count += 1;
        }
        int remove() {
            if ( count == 0 ) _Accept( insert ); // move to main
            int elem = Elements[front];
            front = ( front + 1 ) % 20;
            count -= 1;
            return elem;
        }
```

```
  private:
    void main() {
        for ( ;; ) {          // INFINITE LOOP!!!
            _Accept( insert || remove ); // no synchronization
            _When ( count != 20 ) _Accept( insert ) {   // after call
            } or _When ( count != 0 ) _Accept( remove ) { // after call
            } // _Accept
        }
    }
};
```

- `_Accept( m1 || m2 ) S1 ≡ _Accept( m1 ) S1; or _Accept( m2 ) S1; // S2`
  `if ( C1 || C2 ) S1 ≡ if ( C1 ) S1; else if ( C2 ) S1; // S2`
- Extended version allows different **_When**/code after call for each accept.
- The **_When** clause is like the condition of conditional critical region:
  - The condition must be true (or omitted) *and* a call to the specified member must exist before a member is accepted.
- If all the accepts are conditional and false, the statement does nothing (like **switch** with no matching **case**).
- If some conditionals are true, but there are no outstanding calls, the acceptor is blocked until a call to an appropriate member is made.
- If several members are accepted and outstanding calls exist to them, a call is selected based on the order of the **_Accept**s.
  - Hence, order of **_Accept**s indicates relative selection priority when several outstanding calls.
- Is there a potential starvation problem?
- Why are accept statements moved from member routines to the task main?
- Why is BoundedBuffer::main defined at the end of the task?
- Equivalence using **if** statements:

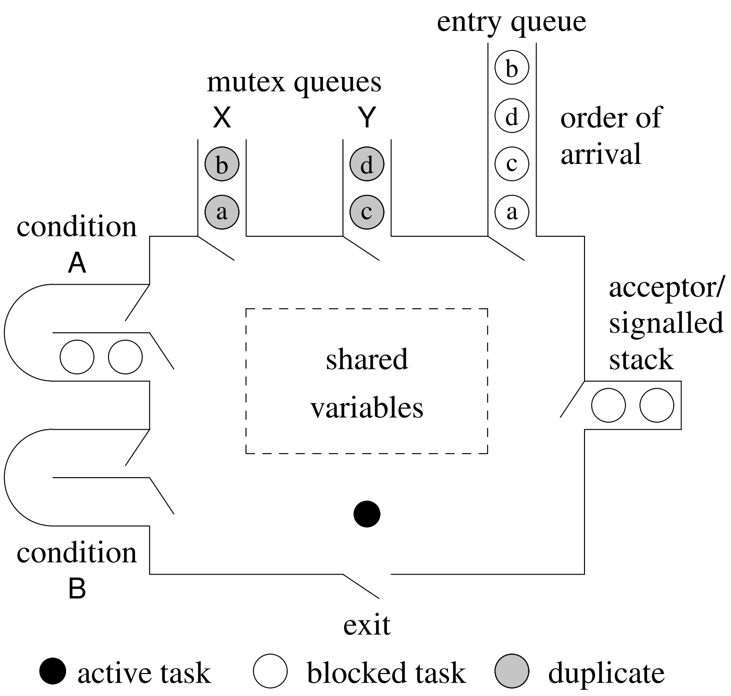
```
if ( 0 < count && count < 20 ) _Accept( insert || remove ); // not full/empty
else if ( count < 20 ) _Accept( insert ); // not full
else /* if ( 0 < count  ) */ _Accept( remove ); // not empty
```

- Generalize from 2 to 3 conditionals/members:

```
if        ( C1 && C2 && C3 ) _Accept( M1 || M2 || M3 );
else if   ( C1 && C2 ) _Accept( M1 || M2 );
else if   ( C1 && C3 ) _Accept( M1 || M3 );
else if   ( C2 && C3 ) _Accept( M2 || M3 );
else if   ( C1 ) _Accept( M1 );
else if   ( C2 ) _Accept( M2 );
else if   ( C3 ) _Accept( M3 );
```

- Necessary to ensure that for every true conditional, only the corresponding members are accepted.
- $2^N - 1$ **if** statements needed to simulate N accept clauses.

- Acceptor pushed on top of the A/S stack and normal implicit scheduling occurs (C < W < S).



- Once accepted call completes or caller wait()s, the statement after the accepting **_Accept** clause is executed and the accept statement is complete.

- If there is a terminating **_Else** clause and no **_Accept** can be executed immediately, the terminating **_Else** clause is executed.

```
_Accept( ... ) {
} or _Accept( ... ) {
} _Else { ... } // executed if no callers
```

  - Hence, the terminating **_Else** clause allows a conditional attempt to accept a call without the acceptor blocking (tryacquire).

- To achieve greater concurrency in the bounded buffer, change to:

```
void insert( int elem ) {
    Elements[back] = elem;
}
int remove() {
    return Elements[front];
}
```

```
private:
   void main() {
        for ( ;; ) {
             _When ( count != 20 ) _Accept( insert ) {
                  back = (back + 1) % 20;
                  count += 1;
             } or _When ( count != 0 ) _Accept( remove ) {
                  front = (front + 1) % 20;
                  count -= 1;
             } // _Accept
        }
   }
```

9.2.2 Internal Scheduling

- Scheduling among tasks inside the monitor.
- As for monitors, condition, signal and wait are used.

```
_Task BoundedBuffer {
     uCondition full, empty;
     int front = 0, back = 0, count = 0;
     int Elements[20];
  public:
     _Nomutex int query() const { return count; }
     void insert( int elem ) {
          if ( count == 20 ) empty.wait();
          Elements[back] = elem;
          back = ( back + 1 ) % 20;
          count += 1;
          full.signal();
     }
     int remove() {
          if ( count == 0 ) full.wait();
          int elem = Elements[front];
          front = ( front + 1 ) % 20;
          count -= 1;
          empty.signal();
          return elem;
     }
  private:
     void main() {
          for ( ;; ) {
               _Accept( insert || remove );
               // do other work
          }
     }
};
```

- Requires combination of internal and external scheduling.
- **Rendezvous is logically pending when wait restarts _Accept task, but post _Accept statement still executed (no RendezvousFailure).**

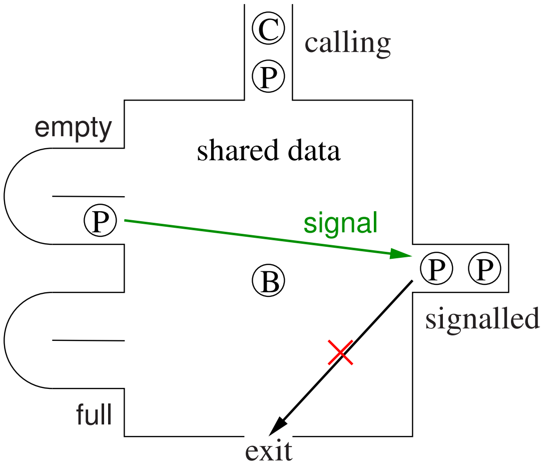
- Acceptor must eventually complete rendezvous for waiting caller.

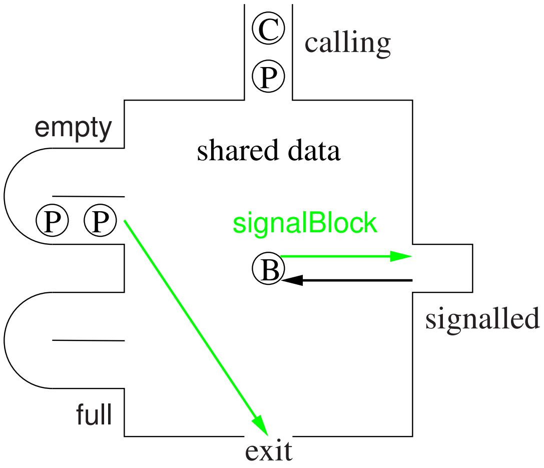
- Try moving code to achieve greater concurrency.

```
        void insert( int elem ) {
            if ( count == 20 ) empty.wait();   // only wait if necessary
            Elements[back] = elem;
        }
        int remove() {
            if ( count == 0 ) full.wait();     // only wait if necessary
            return Elements[front];
        }
    private:
        void postInsert() {                    // helper members
            back = ( back + 1 ) % size;
            count += 1;
        }
        void postRemove() {
            front = ( front + 1 ) % size;
            count -= 1;
        }
        void main() {
            for ( ;; ) {
                _Accept( insert ) {
                    if ( count != 20 ) {       // producer did not wait ?
                        postInsert();
                        if ( ! full.empty() ) { // waiting consumers ?
                            full.signal();     // wake and adjust
                            postRemove();
                        }
                    }
                } or _Accept( remove ) {
                    if ( count != 0 ) {        // consumer did not wait ?
                        postRemove();
                        if ( ! empty.empty() ) { // waiting producers ?
                            empty.signal();    // wake and adjust
                            postInsert();
                        }
                    }
                } // _Accept
            } // for
        }
```

- Must prevent starvation by producers (use **_When** or flip **_Accept** clauses).

- Must change signal to signalBlock.





- ○ Signalled tasks cannot leave because buffer task continues in monitor.
- ○ Signal-blocked tasks leave immediately because buffer-task blocks.

9.2.3 Accepting the Destructor

- Common way to terminate a task is to have a stop member:

```
_Task BoundedBuffer {
  public:
     . . .
     void stop() {} // empty
  private:
     void main() {
          // start up
          for ( ;; ) {
               _Accept( stop ) {   // terminate ?
                    break;
               } or _When ( count != 20 ) _Accept( insert ) {
                    . . .
               } or _When ( count != 0 ) _Accept( remove ) {
                    . . .
               } // _Accept
          }
          // close down
     }
}
```

- Call stop when task is to stop:

```
int main() {
     BoundedBuffer buf;
     // create producer & consumer tasks
     // delete producer & consumer tasks
     buf.stop();  // no outstanding calls to buffer
     // maybe do something with buf (print statistics)
} // delete buf
```

- If termination and deallocation follow one another, accept destructor:

```
void main() {
    for ( ;; ) {
        _Accept( ~BoundedBuffer ) {
            break;
        } or _When ( count != 20 ) _Accept( insert ) { . . .
        } or _When ( count != 0 ) _Accept( remove ) { . . .
        } // _Accept
    }
    // close down
}
```

- However, the semantics for accepting a destructor are different from accepting a normal mutex member.
- When the call to the destructor occurs, the caller blocks immediately if there is thread active in the task because a task's storage cannot be deallocated while in use.
- When the destructor is accepted, the caller is blocked and pushed onto the A/S stack *instead of the acceptor*.
- Therefore, control restarts at the accept statement *without* executing the destructor member.
- Allows mutex object to clean up before termination (monitor or task).
- ***Task now behaves like a monitor because its thread is halted.***
- Only when the caller to the destructor is popped off the A/S stack by the implicit scheduling is the destructor executed.
- The destructor can reactivate any blocked tasks on condition variables and/or the acceptor/signalled stack.

9.3 Increasing Concurrency

- 2 task involved in direct communication: client (caller) & server (callee)
- possible to increase concurrency on both the client and server side

9.3.1 Server Side

- Server manages a resource and server thread should introduce additional concurrency (assuming no return value).

No Concurrency

```
_Task server1 {
  public:
    void mem1(. . .) { S1 }
    void mem2(. . .) { S2 }
    void main() {
        . . .
        _Accept( mem1 );
        or _Accept( mem2 );
    }
}
```

Some Concurrency

```
_Task server2 {
  public:
    void mem1(. . .) { S1.copy–in }
    int  mem2(. . .) { S2.copy–out }
    void main() {
        . . .
        _Accept( mem1 ) { S1.work }
        or _Accept( mem2 ) { S2.work };
    }
}
```

- No concurrency in left example as server is blocked, while client does work.

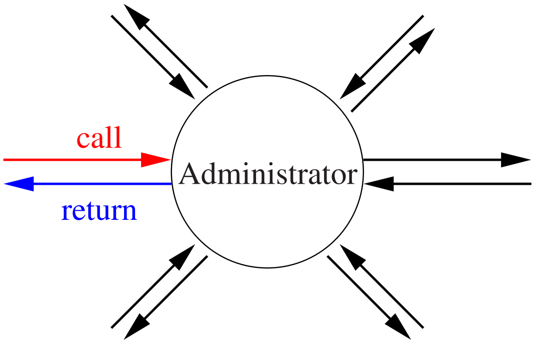
- Alternatively, client blocks in member, server does work, and server unblocks client.
- Some concurrency possible in right example if service can be factored into administrative (`S1.copy`) and work (`S1.work`) code.
  - i.e., move code from the member to statement executed after member is accepted.
- Small overlap between client and server (client gets away earlier) increasing concurrency.

9.3.1.1 Internal Buffer

- The previous technique provides buffering of size 1 between the client and server.
- Use a larger internal buffer to allow clients to get in and out of the server faster?
- I.e., an internal buffer can be used to store the arguments of multiple clients until the server processes them.
- However, there are several issues:
  - Unless the average time for production and consumption is approximately equal with only a small variance, the buffer is either always full or empty.
  - Because of the mutex property of a task, no calls can occur while the server is working, so clients cannot drop off their arguments.
    The server could periodically accept calls while processing requests from the buffer (awkward).
  - Clients may need to wait for replies, in which case a buffer does not help unless there is an advantage to processing requests in non-FIFO order.
- Only way to free server's thread to receive new requests and return finished results to clients is add another thread.
- Additional thread is a **worker task** that calls server to get work from buffer and return results to buffer.
- Note, customer (client), manager (server) and employee (worker) relationship.
- Number of workers has to balance with number of clients to maximize concurrency (bounded-buffer problem).

9.3.1.2 Administrator

- An **administrator** is a server managing multiple clients and worker tasks.
- The key is that an administrator does little or no "real" work; its job is to manage.
- Management means delegating work to others, receiving and checking completed work, and passing completed work on.
- An administrator is called by others, so an administrator is always accepting calls.



- An administrator makes no call to another task because calling may block the administrator.
- An administrator usually maintains a list of work to pass to **worker tasks**.
- Typical workers are:

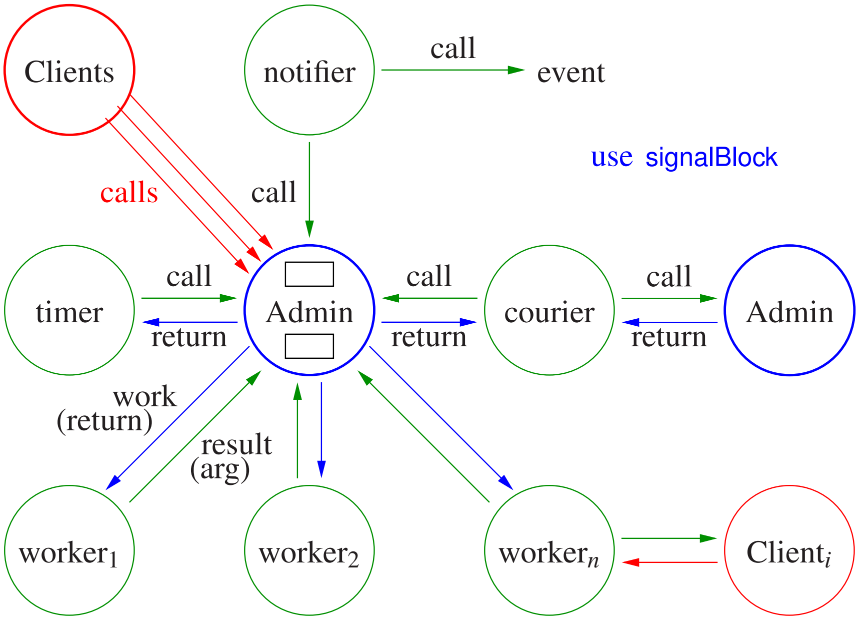
timer - prompt the administrator at specified time intervals

notifier - perform a potentially blocking wait for an external event (key press)

simple worker - do work given to them by and return the result to the administrator

complex worker - do work given to them by administrator and interact directly with client of the work

courier - perform a potentially blocking call on behalf of the administrator



9.3.2 Client Side

- While a server can attempt to make a client's delay as short as possible, not all servers do it.
- In some cases, a client may not have to wait for the server to process a request (producer/consumer problem)

- This can be accomplished by an asynchronous call from the client to the server, where the caller does not wait for the call to complete.
- Asynchronous call requires implicit buffering between client and server to store the client's arguments from the call.
- μC++ provides only synchronous call, i.e., the caller is delayed from the time the arguments are delivered to the time the result is returned (like a procedure call).
- It is possible to build asynchronous facilities out of the synchronous ones and vice versa.

9.3.2.1 Returning Values

- If a client only drops off data to be processed by the server, the asynchronous call is simple.
- However, if a result is returned from the call, i.e., from the server to the client, the asynchronous call is significantly more complex.
- To achieve asynchrony in this case, a call must be divided into two calls:

```
callee.start( arg );          // provide arguments
// caller performs other work asynchronously
result = callee.wait();       // obtain result
```

- Not same as START/WAIT because server thread exists.
  - many-to-one (start/wait) versus one-to-one (START/WAIT)
- Time between calls allows calling task to execute asynchronously with task performing operation on the caller's behalf.
- If result is not ready when second call is made
  - caller blocks
  - caller has to call again (poll).
- However, a protocol is needed to match clients with results in the second call.

9.3.2.2 Tickets

- One form of protocol is the use of a token or ticket.
- The first part of the protocol transmits the arguments specifying the desired work and a ticket (like a dry-cleaning ticket) is returned immediately.
- The second call *pulls* the result by passing the ticket.
- The ticket is matched with a result, and the result is returned if available or the caller is blocks or polls until the result is available.
- However, protocols are error prone because the caller may not obey the protocol (e.g., never retrieve a result, use the same ticket twice, forged ticket).

9.3.2.3 Call-Back Routine

- Another protocol is to transmit (register) a routine on the initial call.
- When the result is ready, the routine is called by the task generating the result, passing it the result.

- The call-back routine cannot block the server; it can only store the result and set an indicator (e.g., V a semaphore) known to the client.
- The original client must *poll* the indicator or block until the indicator is set.
- The advantage is that the server can *push* the result back to the client faster (nagging the client to pickup).
- Also, the client can write the call-back routine, so they can decide to poll or block or do both.

9.3.2.4 Futures

- A **future** provides the same asynchrony as above but without an explicit protocol.
- The protocol becomes implicit between the future and the task generating the result.
- Furthermore, it removes the difficult problem of when the caller should try to retrieve the result.
- In detail, a future is an object that is a subtype of the result type expected by the caller.
- Instead of two calls as before, a single call is made, passing the appropriate arguments, and a future is returned.

```
future = callee.work( arg );           // provide arguments, return future
// perform other work asynchronously
i = future + ...;                      // obtain result, may block if not ready
```

- The future is returned immediately and it is empty.
- The caller "believes" the call completed and continues execution with an empty result value.
- The future is filled in at some time in the "future", when the result is calculated.
- If the caller tries to use the future before its value is filled in, the caller is implicitly blocked.
- The general design for a future is:

```
class Future : public ResultType {
    friend _Task server;      // allow server to access internal state
    ResultType result;        // place result here
    uSemaphore avail;         // wait here if no result
    Future * link;            // intrusive data structure
  public:
    Future() : avail( 0 ) {}

    ResultType get() {
        avail.P();            // wait for result
        return result;
    }
};
```

  - the semaphore is used to block the caller if the future is empty
  - the link field is used to chain the future onto a server work-list.

- Unfortunately, the syntax for retrieving the value of the future is awkward as it requires a call to the get routine.
- Also, in languages without garbage collection, the future must be explicitly deleted.

- μC++ provides two forms of template futures, which differ in storage management (like Actors/Messages).
  - Explicit-Storage-Management future (`Future_ESM<T>`) must be allocated and deallocated explicitly by the client.
  - Implicit-Storage-Management future (`Future_ISM<T>`) automatically allocates and frees storage (when future no longer in use, GC).
- Focus on `Future_ISM` as simpler to use but less efficient in certain cases.
- Basic set of operations for both types of futures, divided into client and server operations.

Client

- Future value:

```
#include <uFuture.h>
Server server;                          // server thread handles async calls
Future_ISM<int> f[10];
for ( int i = 0; i < 10; i += 1 ) {
    f[i] = server.perform( i );         // asynchronous server call
}
// work asynchronously while server processes requests
for ( int i = 0; i < 10; i += 1 ) {     // retrieve async results
    osacquire( cout ) << f[i]() << ' ' << f[i]() + i << endl;
}
f[3]() = 3; // DISALLOWED: OTHER THREADS READING VALUE
. . .
f[3].reset(); // reset future => empty and can be reused (be careful)
. . .
f[3].cancel(); // attempt to stop server and clients from usage
```

- After the future result is retrieved, it can be retrieved again cheaply (no blocking).
- Why is combining `osacquire( cout )` and `f[i]()` dangerous?
- Future pointer:

```
#include <uFuture.h>
Server server;                  // server thread handles async calls
int val
Future_ISM<int *> fval;
fval = server.perform( val );   // async call to server (change val by reference)
// work asynchronously while server processes requests
osacquire( cout ) << *fval() << endl;   // synchronize on retrieve value
val = 3;   // ALLOWED: BUT FUTURE POINTER IS STILL READ-ONLY
```

available – returns **true** if asynchronous call completed, otherwise **false**. complete ⇒ result available, server raised exception, or call cancelled

operator() – (function call) returns ***read-only*** copy of future result.

block if future unavailable; raise exception if exception returned by server.

future result can be retrieved multiple times by any task (⇒ read-only) until the future is reset or destroyed.

`reset` – mark future as empty ⇒ current future value is unavailable ⇒ future can be reused.

`cancel` – attempts to cancel the asynchronous call the future refers to.

Clients waiting for the result are unblocked, and exception of type `uCancelled` is raised at them.

`cancelled` – returns **true** if the future is cancelled and **false** otherwise.

Server

```
_Task Server {
    struct Work {
        int i;                          // argument(s)
        Future_ISM<int> result;         // result
        Work( int i ) : i( i ) {}
    };
    Future_ISM<int> perform( int i ) { // called by clients
        Work *w = new Work( i );        // create work request
        requests.push_back( w );        // add to list of requests
        return w->result;               // return future in request
    }

    // server or server's worker does
    Work *w = requests.front();         // take next work request
    requests.pop_front();               // remove request
    int r = . . . w->i . . .;           // compute result using argument w->i
    w->result.delivery( r );            // insert result into future
    delete w;          // CLIENT FUTURE NOT DELETED (REF COUNTING)
};
```

`delivery( T result )` – copy client result into the future, unblocking clients waiting for the result.

`delivery( uBaseEvent * cause )` – copy exception into the future, and the exception is thrown at waiting clients.

For future to manage exception lifetime, the exception must be dynamically allocated.

```
_Exception E {};
Future_ISM<int> result;
result.delivery( new E );   // deleted by future
```

The exception is implicitly deleted when the future is deleted or reset.

Complex Future Access (client side)

- **select statement** waits for one or more **heterogeneous** futures based on logical selection-criteria.
- Simplest select statement has a single **_Select** clause, e.g.:

  `_Select( selector-expression );`
- Selector-expression must be satisfied before execution continues.

- For a single future, the expression is satisfied if and only if the future is available.

```
_Select( f1 ); // expensive (wait)        ≡    x = f1(); // expensive (wait),
x = f1(); // cheap, value or exception                   // value or exception
```

- Selector is only select blocked until `f1.available()` is true.
- Does not return future value or throw exception.
- Multiple futures may appear in a compound selector-expression, related using logical operators `||` and `&&`:

```
_Select( f1 || f2 && f3 );
```

- Normal operator precedence applies: `_Select( ( f1 || ( f2 && f3 ) ) )`.
- Execution waits until either future `f1` is available or both futures `f2` and `f3` are available.
- Selector-expression is evaulated from left to right, even for operators of equal priority ⇒ when multiple subexpressions are true, the left-most subexpression satisfies the select statement.
- For any selector expression containing an `||` operator, some futures in the expression may be unavailable after the selector expression is satisfied.
- E.g., in the above, if future `f1` becomes available, neither, one or both of `f2` and `f3` may be available.
- **or** and **and** keywords relate the **_Select** clauses like operators `||` and `&&` relate futures in a select-expression, including precedence.

```
_Select( f1 || f2 && f3 );  ≡  _Select( f1 )
                               or _Select( f2 )
                               and _Select( f3 );
```

- Parentheses may be used to specify evaluation order.

```
_Select( ( f1 || ( f2 && f3 ) ) )  ≡  ( _Select( f1 )
                                      or ( _Select( f2 )
                                      and _Select( f3 ) ) );
```

- A **_Select** clause may be guarded with a logical expression and have code executed after a future receives a value:

```
_When ( conditional-expression ) _Select( f1 )
     statement-1                       // action, future available
or
     _When ( conditional-expression ) _Select( f2 )
          statement-2                  // action, future available
     and _When ( conditional-expression ) _Select( f3 )
          statement-3                  // action, future available
```

- Each **_Select**-clause action is executed when its sub-selector expression is satisfied, i.e., when each future becomes available.
- However, control does not continue until the selector expression associated with the entire statement is satisfied.
- E.g., if `f2` becomes available, statement-2 is executed but the selector expression for the entire statement is **not** satisfied so control blocks again.

- When either f1 or f3 become available, statement-1 or 3 is executed, and the selector expression for the entire statement is satisfied so control continues.
- If a guard is false, execution continues without waiting for that future to become available.

```
_When( true ) _Select( f1 ) {...}                  _When( true ) _Select( f1 ) {...}
or                                                 or
    _When( false )
    and                                    ≡
    _When( true ) _Select( f3 ) {...}                  _When( true ) _Select( f3 ) {...}
```

  Assume only f3 becomes available, execution continues.

- An action statement is triggered only once for its selector expression, even if the selector expression is compound.

```
_Select( f1 )
     statement-1
or _Select( f2 && f3 )
     statement-2              // triggered once after both available
```

- In statement-2, both futures f2 and f3 are available.
- However, for ||:

```
_Select( f1 || f2 )
     statement-1              // triggered once after one available
and _Select( f3 )
     statement-2
```

- In statement-1, only one future f1 or f2 caused the action to be triggered.
- Hence, it is necessary to check which of the two futures is available.
- A select statement can be non-blocking using a terminating **_Else** clause, e.g.:

```
_Select( selector-expression )
    statement                          // action
_When ( conditional-expression ) _Else   // terminating clause
    statement                          // action
```

- The **_Else** clause *must* be the last clause of a select statement.
- If its guard is true or omitted and the select statement is not immediately true, then the action for the **_Else** clause is executed and control continues.
- If the guard is false, the select statement blocks as if the **_Else** clause is not present.
- Complex synchronization: wait for 3 different events or 1 to stop.

```
Future_ISM<int> fi;
Future_ISM<double> fd;
struct Msg { int i, j; }; Future_ISM<Msg> fm;
struct Stop {}; Future_ISM<Stop> fs;
struct Cont {}; Future_ISM<Cont> fc;
_Task Worker {
    void main() {
        for ( ;; ) {
            _Select( fi ) { cout << fi() << endl; fi.reset(); }
            and _Select( fd ) { cout << fd() << endl; fd.reset(); }
            and _Select( fm ) { cout << fm()->i << " " << fm()->j << endl; fm.reset(); }
            or _Select( fs ) { cout << "stop" << endl; break; }
            fc.delivery( (Cont){} );            // synchronize
        }
    }
};
int main() {
    Worker worker;
    for ( int i = 0; i < 10; i += 1 ) {
        fi.delivery( i );
        fd.delivery( i + 2.5 );
        fm.delivery( (Msg){ i, 2 } );
        fc(); fc.reset();                        // wait for 3 futures to be processed
    }
    fs.delivery( (Stop){} );
} // wait for worker to terminate
```

10 Optimization

- A computer with infinite memory and speed requires no optimizations to use less memory or run faster (space/time).
- With finite resources, optimization is useful/necessary to conserve resources and for good performance.
- Furthermore, most programs are not written in optimal order or in minimal form.
  - OO, Functional, SE are seldom optimal approaches on von Neumann machine.
- General forms of optimizations are:
  - **reordering**: data and code are reordered to increase performance in certain contexts.
  - **eliding**: removal of unnecessary data, data accesses, and computation.
  - **replication**: processors, memory, data, code are duplicated because of limitations in processing and communication speed (speed of light).
- Optimized program must be isomorphic to original ⇒ produce same result for fixed input.
- Kinds of optimizations are restricted by the kind of execution environment.

10.1 Sequential Optimizations

- Most programs are sequential; even concurrent programs are
  - (large) sections of sequential code per thread connected by
  - small sections of concurrent code where threads interact (protected by synchronization and mutual exclusion (SME))
- ***Sequential*** execution presents simple semantics for optimization.
  - operations occur in **program order**, i.e., sequentially
- Dependencies result in partial ordering among a set of statements (precedence graph):
  - **data dependency** (R ⇒ read, W ⇒ write)

$R_x \rightarrow R_x$	$W_x \rightarrow R_x$	$R_x \rightarrow W_x$	$W_x \rightarrow W_x$
`y = x;` `z = x;`	`x = 0;` `y = x;`	`y = x;` `x = 3;`	`x = 0;` `x = 3;`

    Which statements can be reordered?

  - **control dependency**

```
1   if ( x == 0 )
2       y = 1;
```

    Statements cannot be reordered as line 1 determines if 2 is executed.

- To achieve better performance, compiler/hardware make changes:
  1. reorder disjoint (independent) operations (**variables have different addresses**)

$R_x \rightarrow R_y$	$W_x \rightarrow R_y$	$R_x \rightarrow W_y$	$W_x \rightarrow W_y$
`t = x;` `s = y;`	`x = 0;` `y == 1;`	`x == 1;` `y = 3;`	`y = 0;` `x = 3;`

Which statements can be reordered?

2. elide unnecessary operations (transformation/dead code)

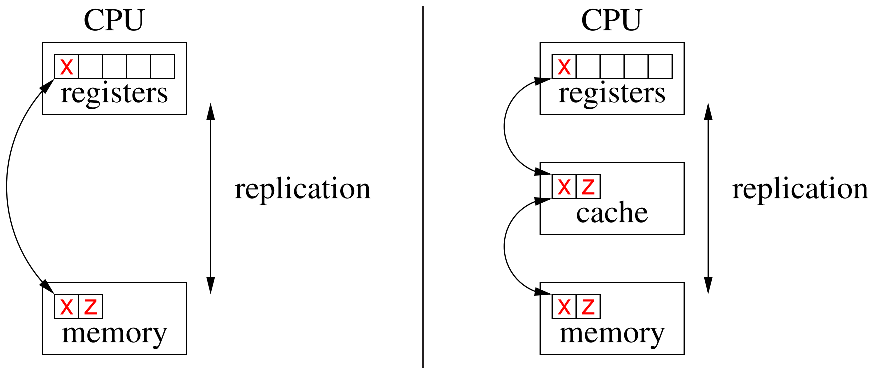
```
x = 0;   // unnecessary, immediate change
x = 3;

for ( int i = 0; i < 10000; i += 1 ); // unnecessary, no loop body

int factorial( int n, int acc ) {   // tail recursion
    if (n == 0) return acc;
    return factorial( n - 1, n * acc ); // convert to loop
}
```

3. execute in parallel if multiple functional-units (adders, floating units, pipelines, cache)

- Very complex reordering, reducing, and overlapping of operations allowed.
- Overlapping implies micro-parallelism, ***but limited capability in sequential execution.***

10.2 Memory Hierarchy

- Complex memory hierarchy:



- Optimizing data flow along this hierarchy defines a computer's speed.
- Hardware aggressively optimizes data flow for sequential execution.
- Having basic understanding of cache is essential to understanding performance of both sequential and concurrent programs.

10.2.1 Cache Review

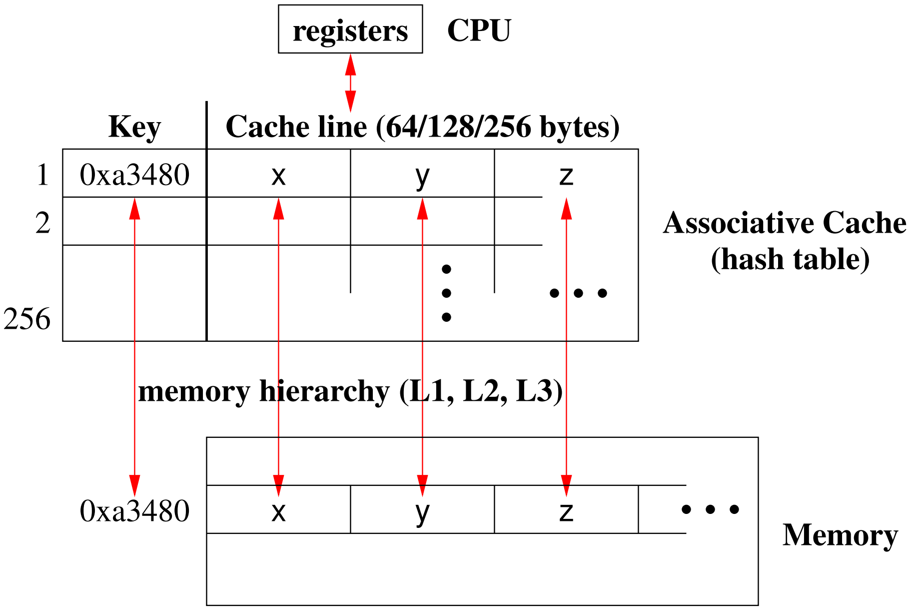
- Problem: CPU 100(0) times faster than memory (100,00(0) times faster than disk).
- Solution: copy data from general memory into very, very fast local-memory (registers).
- Problem: billions of bytes of memory but only 6–256 registers.
- Solution: move highly accessed data ***within*** a program from memory to registers for as long as possible and then back to memory.
- Problem: quickly run out of registers as more data accessed.
  - ◦ ⇒ must rotate data from memory through registers dynamically.

  - ◦ compiler attempts to keep highly used variables in registers (LRU, requires oracle)

- Problem: does not handle highly accessed data ***among*** programs (threads).
  - ◦ each context switch saves and restores most registers to memory
  - ◦ registers are private and cannot be shared

- Solution: use hardware **cache** (automatic registers) to stage data without pushing to memory and allow sharing of data among programs.

```
int x, y, z;
x += 1;     ld   r1,0xa3480     // load register 1 from x
            add  r1,#1          // increment
            st   r1,0xa3480     // store register 1 to x
```



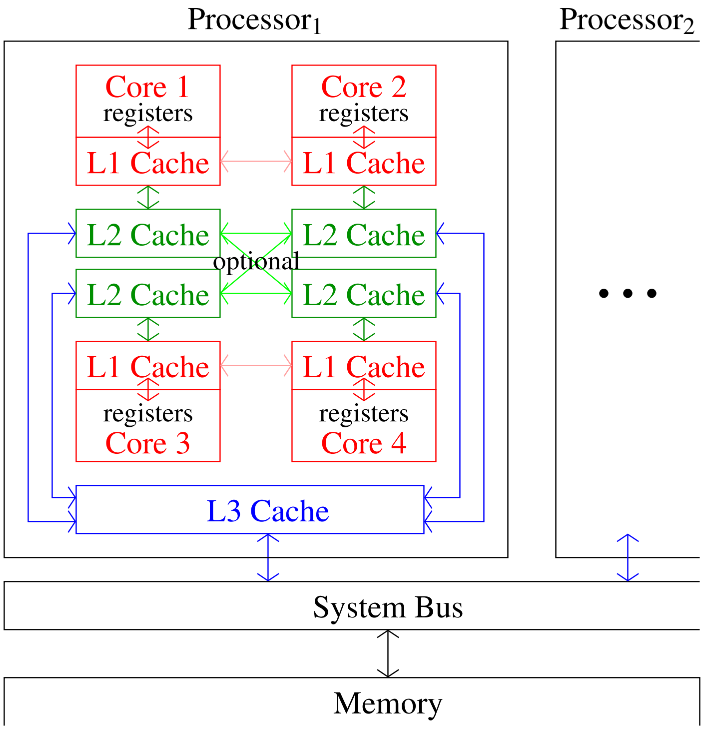
  - ◦ Caching transparently hides the latency of accessing main memory.
  - ◦ Cache loads in 64/128/256 bytes, called **cache line**, with addresses multiple of line size.
  - ◦ When `x` is loaded into register 1, a cache line containing `x`, `y`, and `z` are implicitly copied up the memory hierarchy from memory through caches.
  - ◦ When cache is full, data evicted, i.e., remove old cache-lines to bring in new (LRU).
  - ◦ When program ends, its addresses are flushed from the memory hierarchy.

- In theory, cache can eliminate registers, but registers provide small addressable area (register window) with short addresses (3–8 bits for 8–256 registers) ⇒ shorter instructions.

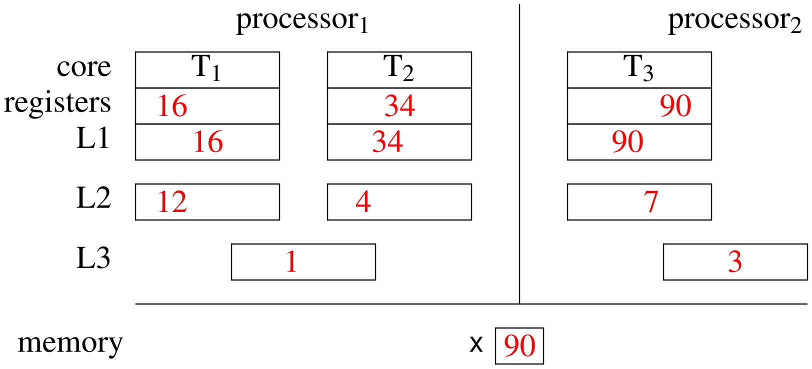
10.2.2 Cache Coherence

- Multi-level caches used, each larger but with diminishing speed (and cost).

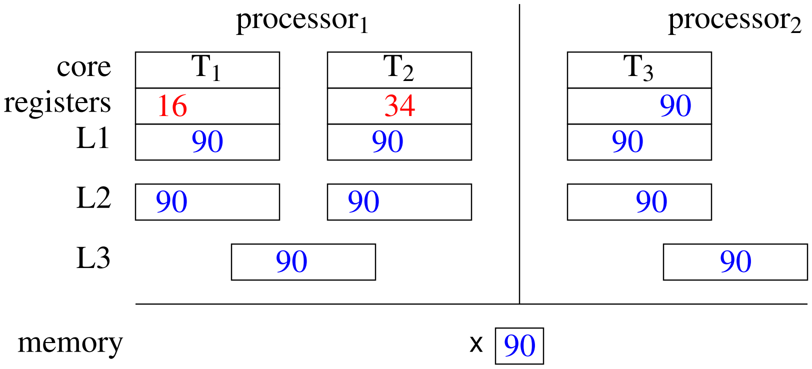
- E.g., 64K L1 cache (32K Instruction, 32K Data) per core, 256K L2 cache per core, and 8MB L3 cache shared across cores.



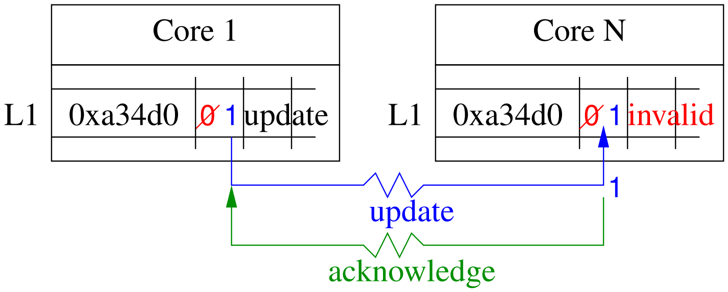
- Data reads logically percolate variables from memory up the memory hierarchy, making cache copies, to registers.
- Why is it necessary to eagerly move reads up the memory hierarchy?
- Data writes from registers to variables logically percolate down the memory hierarchy through cache copies to memory.
- Why is it advantageous to lazily move writes down the memory hierarchy?
- If OS moves program to another processor, all caching information is invalid and the program's data-hierarchy reforms.
- Unlike registers, *all* cache values are shared across the computer.
- Hence, variable can be replicated in a large number of locations.
- Without cache coherence for shared variable x (madness)



- With cache coherence (snooping or directory-based) for shared variable x



- **Cache coherence** is hardware protocol ensuring update of duplicate data.
- **Cache consistency** addresses ***when*** processor sees update ⇒ bidirectional synchronization.
- **Prevent flickering and scrambling during simultaneous R/W or W/W.**



- Eager cache-consistency means data changes appear instantaneous by waiting for acknowledge from all cores (complex/expensive).
- Lazy cache-consistency allows reader to see own write before acknowledgement ⇒ **concurrent programs read stale data!**
  - writes eventually appear in (largely) same order as written
  - critical section works as writes to shared variable appear before write to lock release
  - otherwise, spin (lock) until write appears
- If threads continually read/write same memory locations, they invalidate duplicate cache lines, resulting in excessive cache updates.
  - called **cache thrashing**
  - updated value bounces from one cache to the next
- Because cache line contains multiple variables, cache thrashing can occur inadvertently, called **false sharing**.
- Thread 1 read/writes x while Thread 2 read/writes y ⇒ no direct shared access, but indirect sharing as x and y share cache line.
  - Fix by separating x and y with sufficient storage (padding) to be in next cache line.
  - Difficult for dynamically allocated variables as memory allocator positions storage.

```
thread 1              thread 2
int *x = new int      int *y = new int;
```

x and y may or may not be on same cache line.

10.3 Concurrent Optimizations

- In sequential execution, **strong memory ordering**: reading always returns last value written.
- In concurrent execution, **weak memory ordering**: reading can return previously written value or value written in future.
  - happens on multi-processor because of scheduling and buffering (see scrambling/flickering in Section 5.18.6, p. 83 and freshness/staleness in Section 6.4.4.4, p. 120).
  - notion of ***current*** value becomes blurred for shared variables unless everyone can see values assigned simultaneously.
- SME control order and speed of execution, otherwise non-determinism causes random results or failure (e.g., race condition, Section 7.1, p. 129).
- Sequential sections accessing private variables can be optimized normally ***but not across concurrent boundaries***.
- Concurrent sections accessing shared variables can be corrupted by sequential optimizations ⇒ restrict optimizations to ensure correctness.
- For correctness and performance, identify concurrent code and only restrict *its* optimization.
- What/how to restrict depends on what sequential assumptions are implicitly applied by hardware and compiler (programming language).
- Following examples show how sequential optimizations cause failures in concurrent code.

10.3.1 Disjoint Reordering

- $R_x \rightarrow R_y$ allows $R_y \rightarrow R_x$
  Reordering disjoint reads does not cause problems. Why?
- $W_x \rightarrow R_y$ allows $R_y \rightarrow W_x$
  - In Dekker entry protocol (see Section 5.18.6, p. 83)

```
1   me = WantIn; // W
2   while ( you == WantIn ) { // R
3       . . .
```

```
    temp = you; // R
1   me = WantIn; // W
2   while ( temp == WantIn ) {
3       . . .
```

  both threads read DontWantIn, both set WantIn, both see DontWantIn, and proceed.

- $R_x \rightarrow W_y$ allows $W_y \rightarrow R_x$
  - In synchronization flags (see Section 5.12, p. 77), allows interchanging lines 1 & 3 for Cons:

```
        Cons
1   while ( ! Insert ); // R
2   Insert = false;
3   data = Data; // W
```

```
        Cons
3   data = Data; // W
1   while ( ! Insert ); // R
2   Insert = false;
```

  allows reading of uninserted data

- $W_x \rightarrow W_y$ allows $W_y \rightarrow W_x$
  - In synchronization flags (see Section 5.12, p. 77), allows interchanging lines 1 & 2 in Prod and lines 3 & 4 in Cons:

```
           Prod                   |            Prod
1   Data = i; // W                |  2   Insert = true; // W
2   Insert = true; // W           |  1   Data = i; // W
```

allows reading of uninserted data

- ◦ In Peterson's entry protocol, allows interchanging lines 1 & 2 (see Section 5.18.7, p. 85):

```
1   me = WantIn; // W      |   2   ::Last = &me; // W
2   ::Last = &me; // W     |   1   me = WantIn; // W
```

allows race before either task sets its intent and both proceed

- Compiler uses all of these reorderings to break mutual exclusion:

```
lock.acquire()          // critical section       lock.acquire()
// critical section     lock.acquire()            lock.release();
lock.release();         lock.release();           // critical section
```

- ◦ moves lock entry/exit after/before critical section because entry/exit variables not used in critical section.
- ◦ E.g., **double-check locking** for *concurrent* singleton-pattern:

```
int * ip = nullptr;                 // shared (volatile for correctness)
. . .
if ( ip == nullptr ) {              // no storage ?
    lock.acquire();                 // attempt to get storage (race)
    if ( ip == nullptr ) {          // still no storage ? (double check)
        ip = new int( 0 );          // obtain and initialize storage
    }
    lock.release();
}
```

Why do the first check? Why do the second check?

- ◦ Fails if last two writes are reordered, W_{malloc} and W_{ip}, disjoint variables:

```
call    malloc                  // new storage address returned in r1
st      #0,(r1)                 // initialize storage
st      r1,ip                   // initialize pointer
```

see `ip` but uninitialized.

10.3.2 Eliding

- For high-level language, compiler decides when/which variables are loaded into registers and for how long.
- Elide reads (loads) by copying (replicating) value into a register:

```
      Task1                        Task2
. . .                           register = flag; // one read, auxiliary variable
flag = false // write           while ( register ); // cannot see change by T1
```

- Hence, variable logically disappears for duration in register.
- ⇒ task spins forever in busy loop if R before W.
- Also, elide meaningless sequential code:

```
sleep( 1 ); // unnecessary in sequential program
```

⇒ task misses signal by not delaying

10.3.3 Replication

- Why is there a benefit to reorder R/W?
- Modern processors increase performance by executing multiple instructions in parallel (data flow, precedence graph (see 6.4.1)) on **replicated hardware**.
    - internal pool of instructions taken from program order
    - begin simultaneous execution of instructions with inputs
    - collect results from finished instructions
    - feed results back into instruction pool as inputs
    - ⇒ instructions with independent inputs execute out-of-order
- From sequential perspective, disjoint reordering is ***unimportant***, so hardware starts many instruction simultaneously.
- From concurrent perspective, disjoint reordering is ***important***.

10.4 Memory Model

- Manufacturers define set of optimizations performed implicitly by processor.
- Set of optimizations indirectly define a **memory model**.

Relaxation Model	W → R	R → W	W → W	Lazy cache update
atomic consistent (AT)				
sequential consistency (SC)				√
total store order (TSO)	√			√
partial store order (PSO)	√	√		√
weak order (WO)	√	√	√	√
release consistency (RC)	√	√	√	√

- AT has events occur instantaneously ⇒ slow or impossible (distributed).
- SC accepts all events cannot occur instantaneously ⇒ may read old values
- SC still strong enough for software mutual-exclusion (Dekker 5.18.6 / Peterson 5.18.7).
    - SC often considered minimum model for concurrency.
- No hardware supports just AT/SC.
    - TSO (x86/SPARC), PSO, WO (ARM, Alpha), RC (PowerPC) + atomic R/W synchronizations

10.5 Preventing Optimization Problems

- All optimization problems result from races on shared variables.
- If shared data is protected by locks (implicit or explicit),
    - locks define the sequential/concurrent boundaries,
    - boundaries must preclude optimizations that affect concurrency.
- Called **race free** as synchronization and mutual exclusion preclude races.

- However, race free does have races.

- Races are internal to locks, which lock programmer must deal with.

- Two approaches:
  - ad hoc: programmer manually augments all data races with pragmas to restrict compiler/hardware optimizations: not portable but often optimal.
  - formal: language has memory model and mechanisms to abstractly define races in program: portable but often baroque and suboptimal.

- data access / compiler (C/C++): **volatile** qualifier
  - Force variable loads and stores to/from registers (at **sequence points**)
  - created for longjmp or force access for memory-mapped devices
  - for architectures with few registers, practically all variables are implicitly volatile. Why?
  - Java **volatile** / C++11 atomic stronger ⇒ prevent eliding ***and*** disjoint reordering ⇒ SC

- program order / compiler (static): disable inlining, **asm**("" ::: "memory");

- memory order / runtime (dynamic): sfence, lfence, mfence (x86)
  - guarantee previous stores and/or loads are completed, before continuing.

- atomic operations test-and-set, which often imply fencing

- cache is normally invisible and does not cause issues (except for DMA)

- mechanisms to fix issues are specific to compiler or platform
  - difficult, low-level, diverse semantics, not portable ⇒ ***tread carefully!***

- Dekker for TSO:

```
#define CALIGN __attribute__(( aligned (64) ))  // cache-line alignment
#define Pause() __asm__ __volatile__ ( "pause" : : : ) // efficient busy wait
enum Intent { WantIn, DontWantIn };
//#define ATOMIC
#ifndef ATOMIC
#define Fence() __asm__ __volatile__ ( "mfence" ) // prevent hardware reordering
typedef volatile Intent VIntent;
typedef volatile Intent * volatile VIntentPtr;
#else
#define Fence()
#include <atomic>
typedef std::atomic<Intent> VIntent;
typedef std::atomic<std::atomic<Intent> *> VIntentPtr;
#endif
```

```
_Task Dekker {
    VIntent & me, & you;
    VIntentPtr & Last;
    void main() {
        for ( unsigned int i = 0; i < 1’000’000; i += 1 ) {
            for ( ;; ) {                        // entry protocol
                me = WantIn;                    // high priority
                Fence();
              if ( you == DontWantIn ) break;
                if ( Last == &me ) {            // high priority ?
                    me = DontWantIn;
                    while ( Last == &me ) Pause();  // low priority
                }
                Pause();
            }
            CriticalSection();                  // critical section
            Last = &me;                         // exit protocol
            me = DontWantIn;
        }
    }
  public:
    Dekker( VIntent & me, VIntent & you, VIntentPtr *& Last ) :
        me(me), you(you), Last(Last) {}
};
int main() {
    VIntent me CALIGN = DontWantIn, you CALIGN = DontWantIn,
    VIntentPtr Last = &me;
    Dekker t0(me, you, Last), t1(you, me, Last);
};
```

- C++ atomic automatically fences shared variables, but can be suboptimal.
- Locks built with these features ensure SC for protected shared variables.
    - **no user races and strong locks ⇒ SC memory model**

11 Other Approaches

11.1 Atomic (Lock-Free) Data-Structure

- **Lock free** data-structure have operations, which are critical sections, but performed without **ownership**.
  - e.g., add/remove node without any blocking duration (operation takes constant atomic time)
- Lock-free is still locking (misnomer) ⇒ spin for conceptual lock ⇒ busy-waiting (starvation).
- If guarantees eventual progress, called **wait free**.

11.1.1 Compare and Set Instruction

- The compare-and-set(assign) instruction performs an atomic compare and conditional assignment CAS (erroneously called compare-and-swap).

```
int Lock = OPEN; // shared

bool CAS( int & val,               |  void Task::main() { // each task does
  int comp, int nval ) {           |      while ( ! CAS( Lock, OPEN, CLOSED ) );
    // begin atomic                |      // critical section
    if ( val == comp ) {           |      Lock = OPEN;
        val = nval;                |  }
        return true;               |
    }                              |
    return false;                  |
    // end atomic                  |
}                                  |
```

  - if compare/assign returns true ⇒ loop stops and lock is set to closed
  - if compare/assign returns false ⇒ loop executes until the other thread sets lock to open
  - Alternative implementation assigns comparison value with the value when not equal.

```
bool CASV( int & val, int & comp, int nval ) {
    // begin atomic
    if ( val == comp ) {
        val = nval;
        return true;
    }
    comp = val;              // return unequal value
    return false;
    // end atomic
}
```

  - Assignment when unequal useful to restart operations with new changed value.

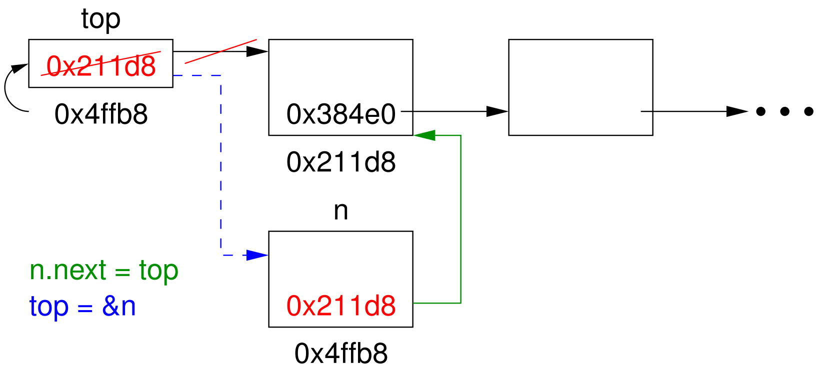
11.1.2 Lock-Free Stack

- E.g., build a stack with lock-free `push` and `pop` operations.

```
class Stack {
        Node * top;                    // pointer to stack top
    public:
        struct Node {
            // data
            Node * next;               // intrusive pointer to next node
        };
        void push( Node & n );
        Node * pop();
};
```

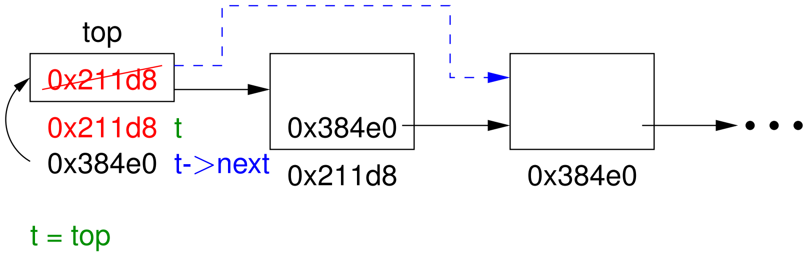
- Use CAS to atomically update top pointer when nodes pushed or popped concurrently.

```
void Stack::push( Node & n ) {
        for ( ;; ) {                   // busy wait
            n.next = top;              // link new node to top node
          if ( CAS( top, n.next, &n ) ) break; // attempt to update top node
        }           // top = &n
}
```



  - Create new node, n, at 0x4ffb8 to be added.
  - Set n.next to top.
  - CAS tries to assign new top &n to top.
  - CAS fails if top changed since copied to n.next
  - If CAS failed, update n.next to top, and try again.
  - CAS succeeds when top == n.next, i.e., no push or pop between setting n.next and trying to assign &n to top.
  - CASV copies changed value to n.next, so eliminates resetting t = top in busy loop.

```
Node * Stack::pop() {
        Node * t;
        for ( ;; ) {                   // busy wait
            t = top;                   // copy current top
          if ( t == nullptr ) return t; // empty list ?
          if ( CAS( top, t, t->next ) ) return t; // attempt to update top node
        }           // top = t->next
}
```



- Copy top node, 0x4ffb8, to t for removal.
- If not empty, attempt CAS to set new top to next node, t->next.
- CAS fails if top changed since copied to t.
- If CAS failed, update t to top, and try again.
- CAS succeeds when top == t->next, i.e., no push or pop between setting t and trying to assign t->next to top.
- CASV copies the changed value into t, so eliminates resetting t = top in busy loop.

11.1.3 ABA problem

- Pathological failure for series of pops and pushes, called **ABA problem**.
- Given stack with 3 nodes:

  top → A → B → C

- Popping task, T_i, sets t to A and dereferenced t->next to get next node B for argument to CAS.
- T_i is now time-sliced **before the CAS**, and while blocked, nodes A and B are popped, and A is pushed again:

  top → A → C *// B is gone!*

- When T_i restarts, CAS successfully removes A as same header before time-slice.
- ***But now incorrectly sets* top *to its next node* B:**

  top → B → ???

  stack is now corrupted!!!

11.1.4 Hardware Fix

- Probabilistic solution for stack exists using double-wide CASVD instruction, which compares and assigns 64/128-bit values for 32/64-bit architectures.

```
bool CASVD( uintS_t &val, uintS_t &comp, uintS_t nval ) {
    // begin atomic
    if ( val == comp ) {        // 64/128-bit compare
        val = nval;             // 64/128-bit assignment
        return true;
    }
    comp = val;                 // 64/128-bit assignment
    return false;
    // end atomic
}
```

- Now, associate counter (ticket) with header node:

```
class Stack {
        union Link {
                struct {                    // 32/64-bit x 2
                        Node * top;         // pointer to stack top
                        uintptr_t count;    // count each push
                };
                uintS_t atom;               // 64/128-bit integer
        } link;
    public:
        struct Node {
                // resource data
                Link next;                  // pointer to next node/count (resource)
        };
        Stack() { link.atom = 0; }
        void push( Node & n );
        Node * pop();
};
```

- Increment counter in push (**only count pushes**) so pop can detect ABA if node re-pushed.

```
void Stack::push( Node & n ) {
        n.next = link;                      // atomic assignment unnecessary
        for ( ;; ) {                        // busy wait
          if ( CASVD( link.atom, n.next.atom, (Link){ &n, n.next.count + 1 }.atom ) ) break;
        }               // link.top = &n, link.count = n.next.count + 1
}
```

  - CASVD used to copy entire header to n.next, as structure assignment (2 fields) is not atomic.
  - In busy loop, copy local idea of top to next of new node to be added.
  - CASVD tries to assign new top-header to (h).
  - If top has not changed since copied to n.next, update top to n (new top), and ***increment counter***.
  - If top has changed, CASVD copies changed values to n.next, so try again.

```
Node * Stack::pop() {
        Link t = link;                      // atomic assignment unnecessary
        for ( ;; ) {                        // busy wait
          if ( t.top == nullptr ) return nullptr; // empty stack ?
          if ( CASVD( link.atom, t.atom, (Link){ t.top->next.top, t.count }.atom ) ) return t.top;
        }               // link.top = t.top->next.top, link.count = t.count
}
```

  - CASVD used to copy entire header to t, as structure assignment (2 fields) is not atomic.
  - In busy loop, check if pop on empty stack and return **nullptr**.
  - If not empty, CASVD tries to assign new top t.top->next.top,t.count to h.
  - If top has not changed since copied to t, update top to t.top->next.top (new top).
  - If top has changed, CASVD copies changed values to t, so try again.

- ABA problem (mostly) fixed:

```
top,3 → A → B → C
```

- Popping task, T_i, has t set to A,3 and dereferenced B from t.top->next in argument of CASVD.
- T_i is time-sliced, and while blocked, nodes A and B are popped, and A is pushed again:

```
    top,4 → A → C    // adding A increments counter
```

- When T_i restarts, CASVD fails as header A,3 not equal top A,4.
- Only probabilistic correct as counter finite (like ticket counter).
  - task T_i is time-sliced and sufficient pushes wrap counter to value stored in T_i's header,
  - node A just happens to be at the top of the stack when T_i unblocks.
  - doubtful if failure arises, given 32/64-bit counter and pathological case.

11.2 Safe Memory Reclamation Problem

- All lock-free data-structures dereference a pointer to copy a link from a node, e.g., pop:

```
    t = top;
    <interrupted>
if ( CAS( top, t, t->next ) ) return t;
```

- However, a thread can be interrupted after copying top (before CAS).
- Another thread removes the top node, frees it, and its storage is returned to the OS.
- The interrupted thread restarts, dereferences t, but that address is invalid ⇒ segment fault.
- Normally, dereference is benign as storage is not removed from the address space (very rare).
- Fixing this life-time problem requires safe memory reclamation (SMR).
  - Complex (100s of lines of code) for advanced data structures (queue, deque, tree).
- All solutions must determinate when a node has no references (like garbage collection).
  - each thread maintains a list of accessed nodes, called **hazard pointers**
  - thread updates its hazard pointers while other threads are reading them
  - thread removes a node by hiding it on a private list and periodically scans the hazard lists of other threads for references to that node
  - if no pointers are found, the node can be freed
- For lock-free stack: x, y, z are memory addresses
  - first thread puts x on its hazard list
  - second thread cannot reuse x, because of hazard list
  - second thread must create new object at different location
  - first thread detects change
- Summary: locking versus lock-free
  - lock-free can only handle limited set of critical sections
    lock can protect arbitrarily complex critical section
  - lock-free has no ownership (hold-and-wait) ⇒ no deadlock
  - lock ownership ⇒ interrupted thread can underutilize critical section
  - lock-free without SMR does not ensure eventual progress (breaks rule 5)
  - no performance difference in general case

11.3 Exotic Atomic Instruction

- VAX computer has instructions to atomically insert and remove a node to/from the head or tail of a circular doubly linked list.

```
struct links {
    links * front, * back;
}
bool INSQUE( links &entry, links &pred ) {     // atomic execution
    // insert entry following pred
    return entry.front == entry.back;          // first node inserted ?
}
bool REMQUE( links &entry ) {                  // atomic execution
    // remove entry
    return entry.front == null;                // last node removed ?
}
```

- MIPS processor has two instructions that generalize atomic read/write cycle: LL (load locked) and SC (store conditional).
    - LL instruction loads (reads) a value from memory into a register, and sets a hardware **reservation** on the memory from which the value is fetched.
    - Register value can be modified, even moved to another register.
    - SC instruction stores (writes) new value back to original or another memory location.
    - However, store is conditional and occurs only if no interrupt, exception, or write has occurred at LL reservation.
    - Failure indicated by setting the register containing the value to be stored to 0.
    - E.g., implement test-and-set with LL/SC:

```
int testSet( int &lock ) {      // atomic execution
    int temp = lock;            // read
    lock = 1;                   // write
    return temp;                // return previous value
}
testSet:                        // register $4 contains pointer to lock
    ll   $2,($4)                // read and lock location
    or   $8,$2,1                // set register $8 to 1 (lock | 1)
    sc   $8,($4)                // attempt to store 1 into lock
    beq $8,$0,testSet           // retry if interference between read and write
    j    $31                    // return previous value in register $2
```

    - Does not suffer from ABA problem.

```
Node * pop( Header &h ) {
    Node * t, next;
    for ( ;; ) {                // busy wait
        t = LL( top );
      if ( t == nullptr ) break;  // empty list ?
        next = t->next
      if ( SC( top, next ) ) break;  // attempt to update top node
    }
    return t;
}
```

  - SC detects any ***change*** to `top`, whereas CAS only detects a specific value change to top (is top not equal to A).
  - LL and SC are not required to match.
  - However, most architectures support weak LL/SC.
    - reservation granularity may be cache line or memory block rather than word
    - no nesting or interleaving of LL/SC pairs, and prohibit memory access between LL/SC.
  - Cannot implement atomic swap of 2 memory locations as two reservations are necessary (register to memory swap is possible).
- Hardware transactional memory allows 4, 6, 8 reservations, e.g., Advanced Synchronization Facility (ASF) proposal in AMD64.
- Like database **transaction** that optimistically executes change, and either commits changes, or rolls back and restarts if interference.
  - `SPECULATE` : start speculative region and clear zero flag ; next instruction checks for abort and branches to retry.
  - `LOCK` : `MOV` instructions indicates location for atomic access, but moves not visible to other CPUs.
  - `COMMIT` : end speculative region
    - if no conflict, make `MOV`s visible to other CPUs.
    - if conflict to any move locations, set failure, discard reservations and restore registers back to instruction following SPECULATE
- Can implement several data structures without ABA problem.
- Software Transactional Memory (STM) allows any number of reservations.
  - atomic blocks of arbitrary size:

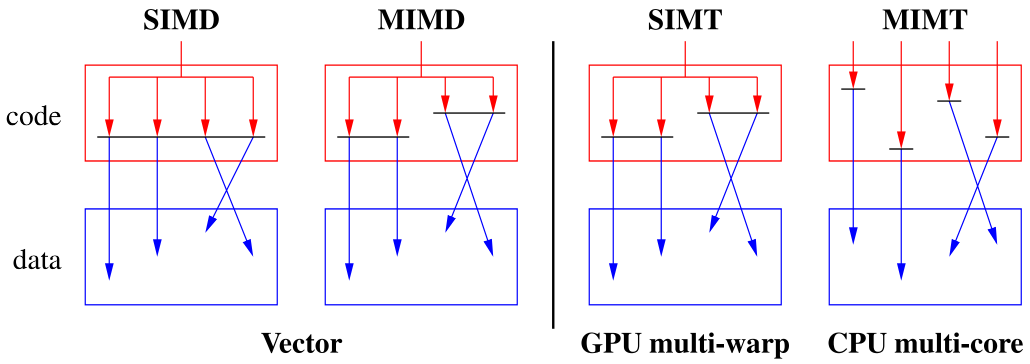
```
void push( header & h, node & n ) {
    atomic {                    // SPECULATE
        n.next = top;           // LOCK/MOV
        top = &n
    }                           // COMMIT
}
```

  - records all memory locations read and written, and all values mutated.
    - bookkeeping costs and rollbacks typically result in performance degradation
  - alternative implementation inserts locks to protect shared access
    - finding all access is difficult and ordering lock acquisition is complex

11.4 General-Purpose GPU (GPGPU)

- Vector processing unit (VPU) is a Single-Instruction Multiple-Data (SIMD) or Multiple-Instruction Multiple-Data (MIMD) architecture.
  - Multi-core CPUs often have small onboard VPU (e.g., x86 advanced vector extension).
- Graphic Processing Unit (GPU) is a **coprocessor** to the main computer, with separate processors and memory.

- GPU is a Single-Instruction Multiple-Thread (SIMT) architecture versus Multiple-Instruction Multiple-Thread (MIMT)



- Certain hardware instructions behave SIMD, e.g., **int** i &= 0x34fe256.

```
ld   r3, i
and  r3, 0x34fe256
st   r3, i
```

  32/64 parallel "ands" in ALU, not looping 64 times "anding" each bit.

- Can i += 1 be SIMD at the instruction level?

- SIMT branching problem (warp divergence): true and false threads must execute same code.

```
if ( a[i] % 2 == 0 ) {
    a[i] /= 2;              // true threads
} else {
    a[i] += 3;              // false threads
}
```

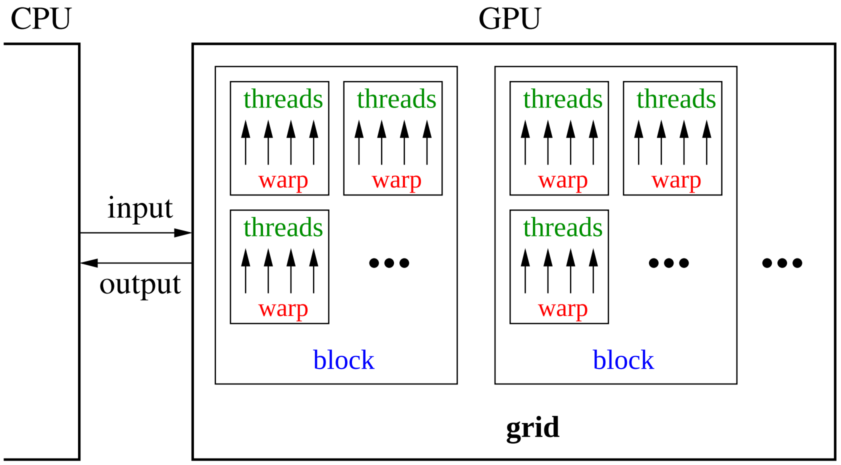
- Flatten solution: Compute both branches and throw away one result.

```
temp0 = a[i] % 2 == 0;   temp1 = a[i] /= 2;   temp2 = a[i] += 3;
a[i] = temp0 ? temp1 : temp2;
```

- Branch solution: all threads test the condition (create mask of true and false)
  - ○ true threads execute "then" instructions, false threads block or execute NOP (no-operation)
  - ○ false threads execute "else" instructions, true threads block or execute NOP

- In general, critical path is time to execute both clauses of **if** in parallel.

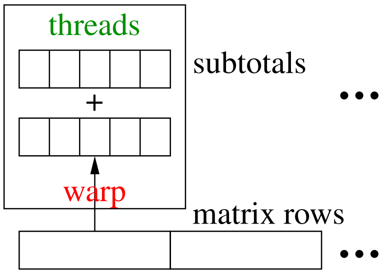
- GPU structure
  - ○ **grid** manages multiple blocks (loaded/controlled by CPU)
  - ○ **block** executes the same code
  - ○ **warp** N-threads executing in lockstep
  - ○ **thread** computes value



  - ○ blocks may be barrier-synchronized
  - ○ synchronization among blocks ⇒ finishing grid and launching new one

- Block threads have a very-fast register set.
- Block threads share fast L1-cache memory.
- Blocks share less-fast L2-cache memory.
- Grid shares slowest global DRAM memory, which stores everything to set up, manage, and return computation.
- Transfering data to/from CPU and global memory is often (PCIe) bus-bound (bottleneck).
- Hence, data layout is an extremely important performance consideration.
- E.g., add rows of a matrix by columns on GPU.

```
// grid routine, handle contiguous matrix, different ID for each thread
grid void GPUsum( float * matrix[], float subtotals[], int rows ) {
#   define sub(m, r, c) ((typeof(m[0][0]) *)m)[r * rows + c]
    subtotals[ID] = 0.0;
    for ( int r = 0; r < rows; r += 1 )
        subtotals[ID] += sub( matrix, r, ID );
}
```



- Block gives eacn warp a row, and warp sums that row in parallel accumulating subtotals.

```
int main() {
    int rows, cols;
    cin >> rows >> cols;        // matrix size
    // optimal to use contiguous matrix
    float matrix[rows][cols], subtotals[rows], total = 0.0;
    // . . . fill matrix
    float * matrix_d, * subtotals_d;            // matrix/subtotals buffer on GPU
    // allocate space on GPU
    GPUMalloc( &matrix_d, sizeof(matrix) );
    GPUMalloc( &subtotals_d, sizeof(subtotals) );
    // copy matrix to GPU
    GPUMemcpy( matrix_d, matrix, sizeof(matrix), GPUMemcpyHostToDevice );
    // compute matrix sum on GPU
    GPUsum<<< 1, cols >>>( matrix_d, substotals_d, rows );
    // do asynchronous work!!!
    // copy subtotals from GPU, may block
    GPUMemcpy( subtotals, subtotals_d, sizeof(subtotals), GPUMemcpyDeviceToHost );
    for ( int i = 0; i < cols; i += 1 ) total += subtotals[i];
    cout << total << endl;
}
```

- ○ CPU allocates GPU global memory,
- ○ copy data/code from CPU memory to GPU global memory,
- ○ request GPU launch code,
- ○ wait for GPU completion,
- ○ copy result from GPU's global memory to CPU's memory.

- Simulate GPU warps with CPU VPU and GPU blocks with concurrency (μC++).

11.5 Concurrency Languages

11.5.1 Ada 95

- Restricted implicit (automatic) signal monitor, e.g., monitor bounded-buffer.

```
protected type buffer is  -- _Monitor
    entry insert( elem : in ElemType ) when count < Size is  -- mutex member
    begin
        -- add to buffer
        count := count + 1;
    end insert;
    entry remove( elem : out ElemType ) when count > 0 is  -- mutex member
    begin
        -- remove from buffer, return via parameter
        count := count - 1;
    end remove;
  private:
    . . . // buffer declarations
    count : Integer := 0;
end buffer;
```

- The **when** clause is only be used at start of entry routine not within.

- The **when** expression can contain only global-object variables; parameter or local variables are disallowed ⇒ no direct dating-service.
- Eliminate restrictions and dating service is solvable.

```
_Monitor DatingService {
    AUTOMATIC_SIGNAL;
    int girls[noOfCodes], boys[noOfCodes]; // count girls/boys waiting
    bool exchange;                        // performing phone-number exchange
    int girlPhoneNo, boyPhoneNo;          // communication variables
  public:
    int girl( int phoneNo, int ccode ) {
        girls[ccode] += 1;
        if ( boys[ccode] == 0 ) {         // no boy waiting ?
            WAITUNTIL( boys[ccode] != 0, , ); // use parameter, not at start
            boys[ccode] -= 1;             // decrement dating pair
            girls[ccode] -= 1;
            girlPhoneNo = phoneNo;        // girl's phone number for exchange
            exchange = false;             // wake boy
        } else {
            girlPhoneNo = phoneNo;        // girl's phone number before exchange
            exchange = true;              // start exchange
            WAITUNTIL( ! exchange, , ); // wait until exchange complete, not at start
        }
        EXIT();
        return boyPhoneNo;
    }
    // boy
};
```

- Threads provided by task object using kernel threads, e.g., task bounded-buffer.

```
task type buffer is  -- _Task
  . . . -- buffer declarations
  count : integer := 0;
begin -- thread starts here (task main)
  loop
    select  -- _Accept
      when count < Size =>  -- guard
      accept insert(elem : in ElemType) do -- mutex member
        -- add to buffer
        count := count + 1;
      end;
      -- executed if this accept called
    or
      when count > 0 =>  -- guard
      accept remove(elem : out ElemType) do -- mutex member
        -- remove from buffer, return via parameter
        count := count - 1;
      end;
    end select;
  end loop;
end buffer;
var b : buffer      -- create a task
```

- **select** is external scheduling and only appears in **task** main.
- Hence, Ada has no direct internal-scheduling mechanism, i.e., no condition variables.
- Instead a **requeue** statement can be used to make a ***blocking*** call to another (usually non-public) mutex member of the object.
- The original call is re-blocked on that mutex member's entry queue, which can be subsequently accepted when it is approriate to restart it.
- However, all **requeue** techniques suffer the problem of dealing with accumulated temporary results:
  - If a call must be postponed, its temporary results must be returned and bundled with the initial parameters before forwarding to the mutex member handling the next step,
  - or the temporary results must be re-computed at the next step (if possible).
- In contrast, waiting on a condition variable automatically saves the execution location and any partially computed state.

11.5.2 SR/Concurrent C++

- SR and Concurrent C++ have tasks with external scheduling using an accept statement.
- But no condition variables or requeue statement.
- To ameliorate lack of internal scheduling add a **when** and by clause on the **accept** statement.
- **when** clause is allowed to reference caller's arguments via parameters of mutex member:

```
select
    accept mem( code : in Integer )
        when code % 2 = 0 do ...     -- accept call with even code
or
    accept mem( code : in Integer )
        when code % 2 = 1 do ...     -- accept call with odd code
end select;
```

- **when** placed after the **accept** clause so parameter names are defined.
- **when** referencing parameter ⇒ implicit search of waiting tasks on mutex queue ⇒ locking mutex queue.
- Select longest waiting if multiple true **when** clauses.
- **by** clause is calculated for each true **when** clause and the **minimum** **by** clause is selected.

```
select
    accept mem( code : in Integer )
        when code % 2 = 0 by −code do ...-- accept largest even code
or
    accept mem( code : in Integer )
        when code % 2 = 1 by code do ...-- accept smallest odd code
end select;
```

- Select longest waiting if multiple by clauses with same minimum.
- **by** clause exacerbates the execution cost of computing **accept** clause.

- While **when/by** removes some internal scheduling and/or requeues, constructing expressions can be complex.
- Still situations that cannot be handled, e.g., if selection criteria involves multiple parameters:
  - select lowest even value of code1 and highest odd value of code2 if there are multiple lowest even values.
  - selection criteria involves information from other mutex queues such as the dating service (girl must search the boy mutex queue).
- Often simplest to unconditionally accept a call allowing arbitrarily examination, and possibly postpone (internal scheduling).

11.5.3 Java

- Java's concurrency constructs are derived from Modula-3.
- Java `Thread` is like μC++ `uBaseTask`, and all tasks must explicitly inherit from it:

```
class Thread implements Runnable {
    public Thread();
    public Thread(String name);
    public String getName();
    public void setName(String name);
    public void run(); // uC++ main
    public synchronized void start();
    public static Thread currentThread();
    public static void yield();
    public final void join();
}
```

- Tasks must explicitly inherit from `Thread`:

```
class MyTask extends Thread {   // inheritance
    private int arg;            // communication variables
    private int result;
    public MyTask() {. . .}     // task constructors
    public void run() {. . .}   // task main
    public int result() {. . .} // return result
    // unusual to have more members
}
```

- Java requires explicit starting of a thread by calling `start` after the thread's declaration.
  ⇒ coding convention to start thread or inheritance is precluded (can only start a thread once)
- Thread starts in member `run` and are kernel threads.
- Termination synchronization is accomplished by calling `join`.
- Returning a result on thread termination is accomplished by member(s) returning values from the task's global variables.

```
mytask th = new MyTask(. . .);  // create and initialized task
th.start();                     // start thread
// concurrency
th.join();                      // wait for thread termination
a2 = th.result();               // retrieve answer from task object
```

- Like μC++, when the task's thread terminates, it becomes an object, hence allowing the call to `result` to retrieve a result.
- (see Section 8.11, p. 151 for monitors)
- While it is possible to have public **synchronized** members of a task:
  - no mechanism to manage direct calls, i.e., no accept statement
  - ⇒ complex emulation of external scheduling with internal scheduling for direct communication
- Java now has "virtual" (light-weight) threads (project Loom) (requires `start` and `join`).

11.5.4 Go

- Non-object-oriented, light-weight (like μC++), preemptive threads (called **goroutine**).
- **go** statement (like start/fork) creates new user thread running in routine.

```
go foo( 3, f )      // start thread in routine foo
```

- Arguments may be passed to goroutine but return value is discarded.
- **Cannot reference goroutine object** ⇒ no direct communication.
- All threads terminate silently when program terminates.
- Threads synchronize/communicate via **channel** (CSP)
  - ⇒ **paradigm shift from routine call**.
- Channel is a typed shared buffer with 0 to N elements.

```
ch1 := make( chan int, 100 )       // integer channel with buffer size 100
ch2 := make( chan string )         // string channel with buffer size 0
ch2 := make( chan chan string )    // channel of channel of strings
```

- Buffer size > 0 ⇒ up to N asynchronous calls; otherwise, synchronous call.
- Operator **<–** performs send/receive.
  - send: `ch1 <– 1      // channel left-hand side`
  - receive: `s <– ch2   // channel right-hand side`
- Channel can be constrained to only send or receive; otherwise bi-directional.
- More like futures and `_Select` with asynchronous call.
- Use synchronous (0-size buffers) to match μC++ synchronous `_Accept`.

```
package main
import "fmt"
func main() {

    type Msg struct{ i, j int }
    ch1 := make( chan int )
    ch2 := make( chan float32 )
    ch3 := make( chan Msg )
    hand := make( chan string )
    shake := make( chan string )
    gortn := func() {
        var i int;  var f float32;  var m Msg
        L: for {
            select {       // wait for messages
              case i = <- ch1: fmt.Println( i )
              case f = <- ch2: fmt.Println( f )
              case m = <- ch3: fmt.Println( m )

              case <- hand: break L // sentinel
            } // select
        } // for
        shake <- "SHAKE" // completion
    } // gortn
    go gortn()              // start thread in gortn
    ch1 <- 0                // different messages
    ch2 <- 2.5
    ch3 <- Msg{1, 2}
    hand <- "HAND" // sentinel value
    <-shake                 // wait for completion
}
```

```
#include <iostream>
using namespace std;
_Task Gortn {
  public:
    struct Msg { int i, j; };
    void mem1( int i ) { Gortn::i = i; }
    void mem2( float f ) { Gortn::f = f; }
    void mem3( Msg m ) { Gortn::m = m; }
  private:
    int i;  float f;  Msg m; // communication
    void main() {

        L: for ( ;; ) {

            _Accept( mem1 ) cout << i << endl;
            or _Accept( mem2 ) cout << f << endl;
            or _Accept( mem3 ) cout << "{" << m.i
                    << " " << m.j << "}" << endl;
            or _Accept( ~Gortn ) break L;

        } // for
    }
}; // Gortn
int main() {
    Gortn gortn;      // start thread in task
    gortn.mem1( 0 );
    gortn.mem2( 2.5 );
    gortn.mem3( (Gortn::Msg){ 1, 2 } );

} // wait for completion
```

- Locks

```
type Mutex                  // mutual exclusion lock
    func (m * Mutex) Lock()
    func (m * Mutex) Unlock()
type Cond                   // synchronization lock
    func NewCond(l Locker) * Cond
    func (c * Cond) Broadcast()
    func (c * Cond) Signal()
    func (c * Cond) Wait()
type Once                   // singleton-pattern
    func (o * Once) Do(f func())
type RWMutex                // readers/writer lock
    func (rw * RWMutex) Lock()
    func (rw * RWMutex) RLock()
    func (rw * RWMutex) RLocker() Locker
    func (rw * RWMutex) RUnlock()
    func (rw * RWMutex) Unlock()
type WaitGroup              // countdown lock
    func (wg * WaitGroup) Add(delta int)
    func (wg * WaitGroup) Done()
    func (wg * WaitGroup) Wait()
```

- Atomic operations

```
func AddInt32(val * int32, delta int32) (new int32)
func AddInt64(val * int64, delta int64) (new int64)
func AddUint32(val * uint32, delta uint32) (new uint32)
func AddUint64(val * uint64, delta uint64) (new uint64)
func AddUintptr(val * uintptr, delta uintptr) (new uintptr)
func CompareAndSwapInt32(val * int32, old, new int32) (swapped bool)
func CompareAndSwapInt64(val * int64, old, new int64) (swapped bool)
func CompareAndSwapPointer(val * unsafe.Pointer, old, new unsafe.Pointer) (swapped bool)
func CompareAndSwapUint32(val * uint32, old, new uint32) (swapped bool)
func CompareAndSwapUint64(val * uint64, old, new uint64) (swapped bool)
func CompareAndSwapUintptr(val * uintptr, old, new uintptr) (swapped bool)
func LoadInt32(addr * int32) (val int32)
func LoadInt64(addr * int64) (val int64)
func LoadPointer(addr * unsafe.Pointer) (val unsafe.Pointer)
func LoadUint32(addr * uint32) (val uint32)
func LoadUint64(addr * uint64) (val uint64)
func LoadUintptr(addr * uintptr) (val uintptr)
func StoreInt32(addr * int32, val int32)
func StoreInt64(addr * int64, val int64)
func StorePointer(addr * unsafe.Pointer, val unsafe.Pointer)
func StoreUint32(addr * uint32, val uint32)
func StoreUint64(addr * uint64, val uint64)
func StoreUintptr(addr * uintptr, val uintptr)
```

11.5.5 C++11 Concurrency

- C++11 std::thread is an OO wrapper over pthreads (use compilation flag -pthread) ⇒ kernel threads.

- Thread creation: start/wait (fork/join) approach.

```
class thread {
  public:
    template <class Fn, class... Args>
        explicit thread( Fn && fn, Args &&... args );
    void join();                      // termination synchronization
    bool joinable() const;            // true => joined, false otherwise
    void detach();                    // independent lifetime
    id get_id() const;                // thread id
};
```

- Passing multiple arguments uses C++11's variadic template feature to provide a type-safe call chain via thread constructor to the *callable* routine.

- Any entity that is *callable* (functor) may be started:

```
#include <thread>
void hello( const string & s ) {          // callable
    cout << "Hello " << s << endl;
}
class Hello {                             // functor
    int result;
  public:
    void operator()( const string & s ) { // callable
        cout << "Hello " << s << endl;
    }
};
int main() {
    thread t1( hello, "Peter" );          // start thread in routine "hello"
    Hello h;                              // thread object
    thread t2( h, "Mary" );               // start thread in functor "h"
    // work concurrently
    t1.join();                            // termination synchronization
    // work concurrently
    t2.join();                            // termination synchronization
} // must join before closing block
```

- Thread starts implicitly at point of declaration.
- Instead of join, thread can run independently by detaching:

```
t1.detach();        // "t1" must terminate for program to end
```

- Beware dangling pointers to local variables:

```
int main() {
    string s( "Fred" );                   // local variable
    thread t( hello, s );                 // reference to s
    t.detach();                           // Free Willy
    pthread_exit( 0 );                    // allows detached threads to continue
} // "s" deallocated and "t" running with reference to "s"
```

- **It is an error to deallocate thread object before join or detach.**
- Locks
  - mutex, recursive, timed, recursive-timed

```
class mutex {
  public:
    void lock();                    // acquire lock
    void unlock();                  // release lock
    bool try_lock();                // nonblocking acquire
};
```

  - condition

```
class condition_variable {
  public:
    void notify_one();              // unblock one
    void notify_all();              // unblock all
    void wait( mutex &lock );       // atomically block & release lock
};
```

- Scheduling is no-priority nonblocking ⇒ barging ⇒ wait statements must be in while loops to recheck conditions.

```
#include <mutex>
class BoundedBuffer {                    // simulate monitor
    // buffer declarations
    mutex mlock;                         // monitor lock
    condition_variable empty, full;
    void insert( int elem ) {
        mlock.lock();
        while (count == Size ) empty.wait( mlock );  // release lock
        // add to buffer
        count += 1;
        full.notify_one();
        mlock.unlock();
    }
    int remove() {
        mlock.lock();
        while( count == 0 ) full.wait( mlock );  // release lock
        // remove from buffer
        count -= 1;
        empty.notify_one();
        mlock.unlock();
        return elem;
    }
};
```

- Futures

```
#include <future>
big_num pi( int decimal_places ) {...}
int main() {
    future<big_num> PI = async( pi, 1200 );  // PI to 1200 decimal places
    // work concurrently
    cout << "PI " << PI.get() << endl;       // block for answer
}
```

- Atomic types/operations
  atomic_flag, atomic_bool, atomic_char, atomic_schar, atomic_uchar, atomic_short, atomic_ushort, atomic_int, atomic_uint, atomic_long, atomic_ulong, atomic_llong, atomic_ullong, atomic_wchar_t, atomic_address, atomic<T>

```
typedef struct atomic_itype {
    bool operator=(int-type) volatile;
    void store(int-type) volatile;
    int-type load() const volatile;
    int-type exchange(int-type) volatile;
    bool compare_exchange(int-type &old_value, int-type new_value) volatile;
    int-type fetch_add(int-type) volatile;
    int-type fetch_sub(int-type) volatile;
    int-type fetch_and(int-type) volatile;
    int-type fetch_or(int-type) volatile;
    int-type fetch_xor(int-type) volatile;
```

```
        int-type operator++() volatile;
        int-type operator++(int) volatile;
        int-type operator--() volatile;
        int-type operator--(int) volatile;
        int-type operator+=(int-type) volatile;
        int-type operator-=(int-type) volatile;
        int-type operator&=(int-type) volatile;
        int-type operator|=(int-type) volatile;
        int-type operator^=(int-type) volatile;
    } atomic_itype;
```

11.6 Threads & Locks Library

11.6.1 java.util.concurrent

- Java library is sound because of memory-model and language is concurrent aware.
- Synchronizers : Semaphore (counting), CountDownLatch, CyclicBarrier, Exchanger, Condition, Lock, ReadWriteLock
- Use new locks to build a monitor with multiple condition variables.

```
class BoundedBuffer {                                       // simulate monitor
    // buffer declarations
    final Lock mlock = new ReentrantLock();                 // monitor lock
    final Condition empty = mlock.newCondition();
    final Condition full = mlock.newCondition();
    public void insert( Object elem ) throws InterruptedException {
        mlock.lock();
        try {
            while (count == Size ) empty.await();   // release lock
            // add to buffer
            count += 1;
            full.signal();
        } finally { mlock.unlock(); } // ensure monitor lock is unlocked
    }
    public Object remove() throws InterruptedException {
        mlock.lock();
        try {
            while( count == 0 ) full.await();   // release lock
            // remove from buffer
            count -= 1;
            empty.signal();
            return elem;
        } finally { mlock.unlock(); } // ensure monitor lock is unlocked
    }
}
```

  - Condition is nested class within ReentrantLock ⇒ condition implicitly knows its associated (monitor) lock.
  - Scheduling is still no-priority nonblocking ⇒ barging ⇒ wait statements must be in while loops to recheck condition.
  - No connection with implicit condition variable of an object.

- ○ **Do not mix implicit and explicit condition variables.**

- Executor/Future : (actors with futures)
  - ○ Executor is a server with one or more worker tasks (worker pool).
  - ○ Future is closure with work for executor (`Callable`) and place for result.
  - ○ Call to executor `submit` is asynchronous and returns a future.
  - ○ Result is retrieved using `get` routine, which may block until result inserted by executor.

```
import java.util.ArrayList;
import java.util.List;
import java.util.concurrent.*;
public class Matrix {
    public static void main( String[] args )
            throws InterruptedException, ExecutionException {
        class Adder implements Callable<Integer> {
            int row[], cols;                        // communication
            public Integer call() {
                int subtotal = 0;
                for ( int c = 0; c < cols; c += 1 ) subtotal += row[c];
                return subtotal;
            }
            Adder( int [] r, int c ) { row = r; cols = c; }
        }
        int rows = 10, cols = 10;
        int matrix[][] = new int[rows][cols], total = 0;
        // read matrix
        ExecutorService executor = Executors.newFixedThreadPool( 4 );
        List<Future<Integer>> subtotals = new ArrayList<Future<Integer>>();
        for ( int r = 0; r < rows; r += 1 )         // send off work for executor
            subtotals.add( executor.submit( new Adder( matrix[r], cols ) ) );
        for ( int r = 0; r < rows; r += 1 )         // wait for results
            total += subtotals.get( r ).get();      // retrieve result
        System.out.println( total );
        executor.shutdown();
    }
}
```

- μC++ also has fixed thread-pool executor (used with actors).

```
struct Adder {                                  // routine, functor or lambda
    int * row, cols;                            // communication
    int operator()() {                          // functor operator
        int subtotal = 0;
        for ( int c = 0; c < cols; c += 1 ) subtotal += row[c];
        return subtotal;
    }
    Adder( int row[ ], int cols ) : row( row ), cols( cols ) {}
};
```

```
int main() {
    const int rows = 10, cols = 10;
    int matrix[rows][cols], total = 0;
    // read matrix
    uExecutor executor( 4 );                // kernel threads
    Future_ISM<int> subtotals[rows];
    Adder * adders[rows];
    for ( int r = 0; r < rows; r += 1 ) {   // send off work for executor
        adders[r] = new Adder( matrix[r], cols );
        subtotals[r] = executor.sendrecv( *adders[r] );
    }
    for ( int r = 0; r < rows; r += 1 ) {   // wait for results
        total += subtotals[r]();
        delete adders[r];
    }
    cout << total << endl;
}
```

- Collections : LinkedBlockingQueue, ArrayBlockingQueue, SynchronousQueue, PriorityBlockingQueue, DelayQueue, ConcurrentHashMap, ConcurrentSkipListMap, ConcurrentSkipListSet, CopyOnWriteArrayList, CopyOnWriteArraySet.
  - Create threads that interact indirectly through atomic data structures, e.g., producer/consumer interact via LinkedBlockingQueue.
- Atomic Types using compare-and-set (see Section 11.1.1, p. 183) (i.e., lock-free). AtomicBoolean, AtomicInteger, AtomicIntegerArray, AtomicLong, AtomicLongArray, AtomicReference<V>, AtomicReferenceArray<E>

```
int v;
AtomicInteger i = new AtomicInteger();
i.set( 1 );
System.out.println( i.get() );
v = i.addAndGet( 1 );           // i += delta
System.out.println( i.get() + " " + v );
v = i.decrementAndGet();        // –i
System.out.println( i.get() + " " + v );
v = i.getAndAdd( 1 );           // i =+ delta
System.out.println( i.get() + " " + v );
v = i.getAndDecrement();        // i–
System.out.println( i.get() + " " + v );
```

```
1
2 2
1 1
2 1
1 2
```

11.6.2 Pthreads

- C libraries built around routine abstraction, mutex/condition locks (“attribute” parameters not shown), and kernel threads.

```
int pthread_create( pthread_t * new_thread_ID,
          void * (* start_func)(void *), void * arg );
int pthread_join( pthread_t target_thread, void ** status );
pthread_t pthread_self( void );
int pthread_yield(void);

int pthread_mutex_init( pthread_mutex_t * mp ); // constructor
int pthread_mutex_lock( pthread_mutex_t * mp );
int pthread_mutex_unlock( pthread_mutex_t * mp );
int pthread_mutex_destroy( pthread_mutex_t * mp ); // destructor

int pthread_cond_init( pthread_cond_t * cp ); // constructor
int pthread_cond_wait( pthread_cond_t * cp, pthread_mutex_t * mutex );
int pthread_cond_signal( pthread_cond_t * cp );
int pthread_cond_broadcast( pthread_cond_t * cp );
int pthread_cond_destroy( pthread_cond_t * cp ); // destructor
```

- Thread starts in routine start_func via pthread_create with single **void** * parameter.

- Termination synchronization is performed by pthread_join with single **void** * result.

```
void * rtn( void * arg ) { . . . }
int i = 3, r, rc;
pthread_t t;                        // thread id
rc = pthread_create( &t, rtn, (void *)i ); // create and initialized task
if ( rc != 0 ) . . .                // check for error
// concurrency
rc = pthread_join( t, &r );         // wait for thread termination and result
if ( rc != 0 ) . . .                // check for error
```

- All C library approaches have type-unsafe communication.

- No external scheduling ⇒ complex direct-communication emulation.

- Internal scheduling is no-priority nonblocking ⇒ barging ⇒ wait statements must be in while loops to recheck conditions

```
typedef struct {                    // simulate monitor
     // buffer declarations
     pthread_mutex_t mutex;         // mutual exclusion
     pthread_cond_t full, empty;    // synchronization
} buffer;
// write your own constructor/destructor
void ctor( buffer * buf ) {         // constructor
     . . .
     pthread_mutex_init( &buf->mutex );
     pthread_cond_init( &buf->full );
     pthread_cond_init( &buf->empty );
}
```

```
void dtor( buffer * buf ) {                    // destructor
    pthread_mutex_lock( &buf->mutex ); // must be mutex
    . . .
    pthread_cond_destroy( &buf->empty );
    pthread_cond_destroy( &buf->full );
    pthread_mutex_destroy( &buf->mutex );
}
void insert( buffer * buf, int elem ) {
    pthread_mutex_lock( &buf->mutex );
    while ( buf->count == Size )
        pthread_cond_wait( &buf->empty, &buf->mutex );
    // add to buffer
    buf->count += 1;
    pthread_cond_signal( &buf->full );
    pthread_mutex_unlock( &buf->mutex );
}
int remove( buffer * buf ) {
    pthread_mutex_lock( &buf->mutex );
    while ( buf->count == 0 )
        pthread_cond_wait( &buf->full, &buf->mutex );
    // remove from buffer
    buf->count -= 1;
    pthread_cond_signal( &buf->empty );
    pthread_mutex_unlock( &buf->mutex );
    return elem;
}
```

- Since there are no constructors/destructors in C, explicit calls are necessary to `ctor`/`dtor` before/after use.
- All locks must be initialized and finalized.
- Mutual exclusion must be explicitly defined where needed.
- Condition locks should only be accessed with mutual exclusion.
- `pthread_cond_wait` atomically blocks thread and releases mutex lock, which is necessary to close race condition on baton passing.

11.7 OpenMP

- Shared memory, implicit thread management (programmer hints), kernel threads, some explicit locking.
- Communicate with compiler with `#pragma` directives.

```
#pragma omp . . .
```

- fork/join model
  - fork: initial thread creates a team of parallel threads (including itself)
  - each thread executes the statements in the region construct
  - join: when team threads complete, synchronize and terminate, except initial thread which continues

- compile: `gcc -std=c99 -fopenmp openmp.c -lgomp`
- COBEGIN/COEND: each thread executes different section:

```
#include <omp.h>
... // declarations of p1, p2, p3
int main() {
    int i;
    #pragma omp parallel sections num_threads( 4 ) // fork "4" threads
    { // COBEGIN
        #pragma omp section
        { i = 1; }                      // BEGIN ... END
        #pragma omp section
        { p1( 5 ); }
        #pragma omp section
        { p2( 7 ); }
        #pragma omp section
        { p3( 9 ); }
    } // COEND (synchronize)
}
```

- **for** directive specifies each loop iteration is executed by a team of threads (COFOR)

```
int main() {
    const unsigned int rows = 10, cols = 10;       // sequential
    int matrix[rows][cols], subtotals[rows], total = 0;
    // read matrix
    #pragma omp parallel for                       // fork "rows" threads
    for ( unsigned int r = 0; r < rows; r += 1 ) { // concurrent
        subtotals[r] = 0;
        for ( unsigned int c = 0; c < cols; c += 1 )
            subtotals[r] += matrix[r][c];
    }
    for ( unsigned int r = 0; r < rows; r += 1 )   // sequential
        total += subtotals[r];
    printf( "total:%d\n", total );
}
```

- In this case, sequential code directly converted to concurrent via #pragma.
- Variables outside section are shared; variables inside are thread private.
- Programmer responsible for sharing in vector/matrix manipulation.
- barrier

```
int main() {
    #pragma omp parallel num_threads( 4 ) // fork "4" threads
    {
        sleep( omp_get_thread_num() );
        printf( "%d\n", omp_get_thread_num() );
        #pragma omp barrier               // wait for all block threads to arrive
        printf( "sync\n" );
    }
}
```

- Without `omp section`, all threads run same block (like `omp parallel` **for**).

- Barrier's trigger is the number of block threads.
- Threads sleeps for different times, but all print `"sync"` at same time.
- Also critical section and atomic directives.

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