An Overview of Multi-threading Mechanisms

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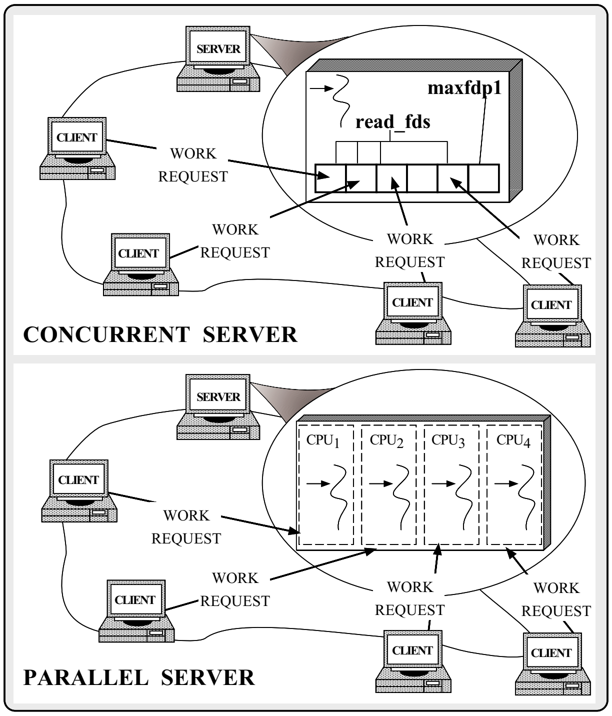
Motivation for Concurrency

- Concurrent programming is increasing relevant to:
  - *Leverage hardware/software advances*
    - ▷ *e.g.*, multi-processors and OS thread support
  - *Increase performance*
    - ▷ *e.g.*, overlap computation and communication
  - *Improve response-time*
    - ▷ *e.g.*, GUIs and network servers
  - *Simplify program structure*
    - ▷ *e.g.*, synchronous vs. asynchronous network IPC

Definitions

- *Concurrency*
  - "Logically" simultaneous processing
  - Does *not* imply multiple processing elements
- *Parallelism*
  - "Physically" simultaneous processing
  - Involves multiple processing elements and/or independent device operations
- Both *concurrency* and *parallelism* require controlled access to shared resources
  - *e.g.*, I/O devices, files, database records, in-core data structures, consoles, etc.

Concurrency vs. Parallelism



Concurrency Overview

- A thread of control is a single sequence of execution steps performed in one or more programs
  - *One program* → standalone systems
  - *More than one program* → distributed systems
- Traditional OS processes contain a single thread of control
  - This simplifies programming since a sequence of execution steps is protected from unwanted interference by other execution sequences...

Traditional Approaches to OS Concurrency

1. Device drivers and programs with signal handlers utilize a limited form of *concurrency*
   - *e.g.*, asynchronous I/O
   - Note that *concurrency* encompasses more than *multi-threading*...
2. Many existing programs utilize OS processes to provide "coarse-grained" concurrency
   - *e.g.*,
     - Client/server database applications
     - Standard network daemons like UNIX `inetd`
   - Multiple OS processes may share memory via memory mapping or shared memory and use semaphores to coordinate execution
   - The OS kernel scheduler dictates process behavior

Evaluating Traditional OS Process-based Concurrency

- Advantages
  - *Easy to keep processes from interfering*
    - ▷ A process combines *security*, *protection*, and *robustness*
- Disadvantages
  1. *Complicated to program*, *e.g.*,
     - Signal handling may be tricky
     - Shared memory may be inconvenient
  2. *Inefficient*
     - The OS kernel is involved in synchronization and process management
     - Difficult to exert fine-grained control over scheduling and priorities

Modern OS Concurrency

- Modern OS platforms typically provide a standard set of APIs that handle
  1. Process/thread creation and destruction
  2. Various types of process/thread synchronization and mutual exclusion
  3. Asynchronous facilities for interrupting long-running processes/threads to report errors and control program behavior
- Once the underlying concepts are mastered, it's relatively easy to learn different concurrency APIs
  - *e.g.*, traditional UNIX process operations, Solaris threads, POSIX pthreads, WIN32 threads, etc.

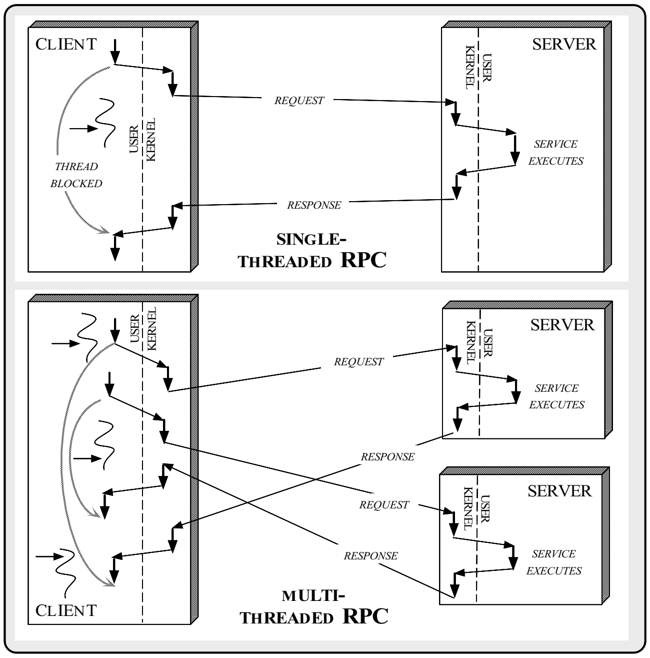
Lightweight Concurrency

- Modern OSs provide lightweight mechanisms that manage and synchronize multiple threads *within* a process
  - Some systems also allow threads to synchronize *across* multiple processes

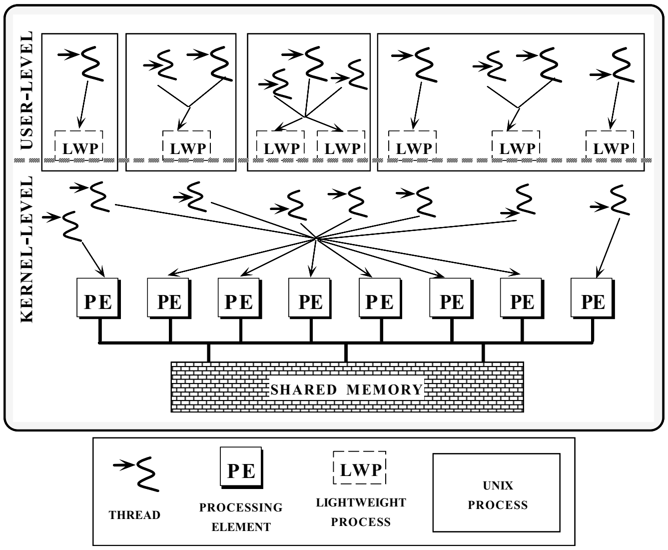
- Benefits of threads

1. *Relatively simple and efficient to create, control, synchronize, and collaborate*
   - Threads share many process resources by default
2. *Improve performance by overlapping computation and communication*
   - Threads may also consume less resources than processes
3. *Improve program structure*
   - *e.g.*, compared with using asynchronous I/O

Single-threaded vs. Multi-threaded RPC



Hardware and OS Concurrency Support



- Modern OS platforms like Solaris provide kernel support for multi-threading

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Kernel Abstractions

- *Kernel threads*
  - The "fundamental scheduling entities" executed by the PE(s)
  - Operate in kernel space
  - Kernel-resident subsystems use kernel threads directly

- *Lightweight processes* (LWP)
  - Every LWP is associated with one kernel thread
    - ▹ *i.e.*, 1-to–1 mapping between kernel thread and LWP per-process
  - Not every kernel thread has an LWP
    - ▹ "System threads" (*e.g.*, pagedaemon, NFS daemon, and the callout thread) have only a kernel thread

Application Abstractions

- *Application threads*
  - LWP(s) can be thought of as "virtual CPUs" on which application threads are scheduled and multiplexed
  - Each application thread has it's own stack
    - ▹ However, it shares its process address space with other threads
  - Application threads are "logically" independent
  - Multiple application threads running on separate LWPs can execute simultaneously (even system calls and page faults...)
    - ▹ Assuming a multi-CPU system or async I/O

Kernel-level vs. User-level Threads

- Application and system characteristics influence the choice of kernel-level vs. user-level threading
- *e.g.*,
  - High degree of "virtual" application concurrency implies user-level threads (*i.e.*, unbound threads)
    - ▹ *e.g.*, desktop windowing system
  - High degree of "real" application parallelism implies lightweight processes (LWPs) (*i.e.*, bound threads)
- In addition, LWPs must be used for:
  - Real-time scheduling class
  - Give thread alternative signal stack
  - Give thread a unique alarm or timer

Performance Considerations

- Performance of different combinations of application-level vs. kernel-level threads is influenced various factors, *e.g.*,
  - Number of PEs
  - Inter-thread communication
  - Inter-thread synchronization
  - Amount of context switching
- It is important to consider the "process architecture" of a multi-threaded application

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Scheduling Classes in SunOS 5.x

- There are three classes of process (LWP) scheduling in SunOS 5.x
  - *Real-time*
    - ▹ Highest priority, the scheduler always dispatches the highest priority real-time LWP
  - *System*
    - ▹ Middle priority
    - ▹ Cannot be applied to a user process
  - *Timesharing* (default)
    - ▹ Lowest priority, provides fair distribution of process resources
- A new process inherits the scheduling class and priority of its parent

Application Thread Overview

- A multi-threaded process contains one or more threads of control
- Each thread may be executed independently and asynchronously
  - Different threads may have different priorities
  - System calls may be made independently, page faults handled separately, etc.
  - Some system calls affect the process
    - ▷ *e.g.*, `exit`
  - Other system calls affect only the calling thread
    - ▷ *e.g.*, `read`/`write`
- Threads in a process are generally invisible to other processes

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Thread Resources

- Most process resources are equally accessible to all threads in the process, *e.g.*,

  * Virtual memory
  * User permissions and access control privileges
  * Open files
  * Signal handlers

- In addition, each thread contains unique information, *e.g.*,

  * Identifier
  * Register set (including PC and SP)
  * Stack
  * Signal mask
  * Priority
  * Thread-specific data (*e.g.*, `errno`)

- Note, there is no MMU protection for separate threads within a single process...

LWP Characteristics

- The threads library uses execution resources called LWPs
  - LWPs are scheduled on top of kernel threads (and PEs) by the OS
  - Likewise, the threads library schedules "unbound" runnable threads on the LWP execution resources
    - ▷ This typically does *not* involve the kernel
- In order to expedite thread operations, LWPs contain certain information that application threads do not have, *e.g.*,
  - *Scheduling class*
    - ▷ *e.g.*, Real-time vs. system vs. timesharing
  - *Alarms*
  - *Interval timers*
  - *Profiling buffers*

Programming LWPs

- The threads library ensures that there are enough LWPs to enable a program to make progress
  - *i.e.*, LWPs may be allocated/deallocated as needed via SIGWAIT signal sent by kernel
- The `thr_setconcurrency` library function provides additional control
  - Note, it is only a hint...
- Note, there is also a low-level interface to the LWP facilities
  - Application programmers typically do not use this interface directly

Thread Creation

- Thread creation is handled via the `thr_create` function:
  - **int** thr_create (**void** *stack_base, size_t stack_size, **void** *(*start_routine)(**void** *), **void** *arg, **long** flags, thread_t *new_thread);
  - `thr_create` creates and starts a new thread using the `start_routine` function specified in the call
    - ▹ Returns 0 on success and non−0 on failure
  - The identify of the thread is returned to the caller
    - ▹ A thread id is only valid within a single process
    - ▹ There is no thread 0...
  - The caller may supply a stack or if a NULL is used the library allocates a default stack

Thread Creation (cont'd)

- `thr_create` (cont'd)
  - Each application thread gets its own stack
  - You may specify a size for the stack or use the default
    - ▹ The default is 1 Megabyte of virtual memory, with no reserved stack space
  - size_t thr_min_stack (**void**)
    - ▹ The size of any stack must be larger than the value of this function call
  - Each stack area is protected with unallocated memory
    - ▹ Thus, if your process overflows the stack a

      bus error (SIGBUS) will occur

Thread Creation (cont'd)

- `thr_create` flags include
  - THR_SUSPENDED
    - ▹ The new thread is created suspended and will not execute the `start_routine` function until it is started by `thr_continue`
  - THR_DETACHED
    - ▹ The new thread is created detached and thread ID and other resources may be reused as soon as the thread terminates
  - THR_BOUND
    - ▹ The new thread is created permanently bound to an LWP

Thread Creation (cont'd)

- `thr_create` flags include
  - THR_NEW_LWP
    - ▹ The desired concurrency level for unbound threads is increased by one, typically by adding a new LWP to the pool of LWPs running unbound threads
  - THR_DAEMON
    - ▹ The thread is marked as a daemon and the process will exit when all non-daemon threads exit
      - · *i.e.*, daemon threads are not counted in the process exit criteria

Differences Between fork and thr_create

- `thr_create` normally allocates a thread stack out of the cache, initializes some fields, and places the thread on the per-process run queue
  - Typically this is not very many instructions, none of them in the kernel
  - The thread will then be run by a CPU when a kernel LWP next checks that queue
- `fork` is quite a bit more heavy weight
  - It creates more new kernel resources than just a new address space

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Thread Exit

- The `thr_exit` function terminates the invoking thread and sets the exit status to the specified value
  - **void** thr_exit (**void** *status);
  - If the thread was *not* detached, its identifier and status are retained until `thr_join` is called via another thread
  - If there are no remaining threads, the process is exited with a 0 exit status...
- The `thr_self` function returns the thread identifier structure of the caller
  - thread_t thr_self (**void**);

Thread Join

- The `thr_join` function blocks until the specified thread exits
  - **int** thr_join (thread_t wait_for, thread_t *departed, **void** **status);
  - If `wait_for` is 0, the functions waits for *any* undetached thread in the process to terminate, else it waits for that `wait_for` thread id to terminate
  - If `departed` is non-NULL it points to location storing the ID of the terminated thread
  - If `status` is non-NULL it points to a location storing the exits status of the terminated thread
  - `thr_join` cannot wait for detached threads, threads in other processes, or the current thread

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Thread Suspend and Resume

- The `thr_suspend` function immediately suspends the specified thread until it is explicitly resumed
  - **int** thr_suspend (thread_t target_thread);
    - ▹ Note, a suspended thread does not receive signals...
- The `thr_continue` function resumes execution of a suspended thread
  - **int** thr_continue (thread_t target_thread);

Thread Scheduling

- The scheduling of threads by the threads library is *non-preemptive*, in the traditional *time-slicing* sense...
  - However, the scheduling of LWPs by the OS *is* preemptive
  - Moreover, LWPs use "priority aging," whereas threads do not...

Thread Scheduling (cont'd)

- **int** thr_setprio (thread_t target_thread, **int** priority);
  - The priority must be >= 0, with greater values indicating increased priority
- **int** thr_getprio (thread_t target_thread)
  - This function gets the thread priority of the specified thread
- **int** thr_yield (**void**);
  - Yields the caller's executing status to any thread with same or higher priority

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Thread Concurrency

- The scheduling of threads is influenced by the following library routines
  - **int** thr_setconcurrency (**int** new_level);
    - ▷ Indicates the desired level of concurrency that application threads require
      - · *i.e.*, number of threads that can be active simultaneously
      - · *i.e.*, the number of LWPs associated with the threads library
    - ▷ Only a hint, actual number of LWPs may be more or less than number requested
  - **int** thr_getconcurrency (void);
    - ▷ Returns current number of LWPs

Synchronization Mechanisms

- Threads share resources in a process address space
- Therefore, they must use *synchronization mechanisms* to coordinate their access to shared data
- Traditional OS synchronization mechanisms are very low-level, tedious to program, error-prone, and non-portable
- ACE encapsulates these mechanisms with higher-level patterns and classes

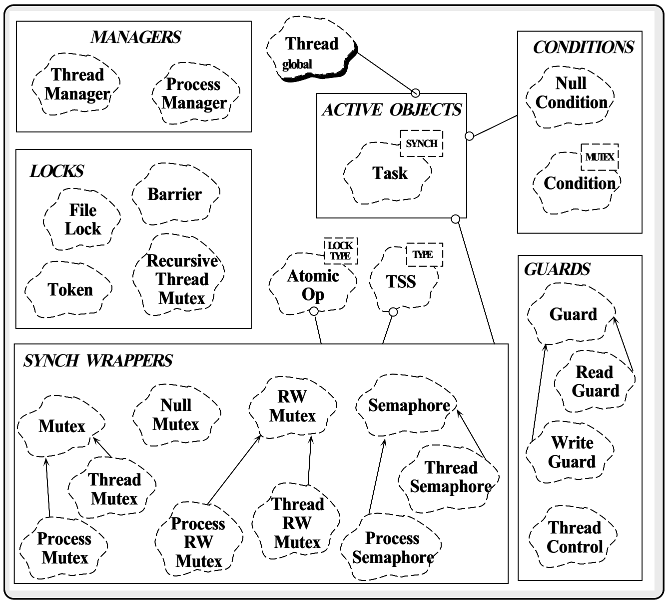
Common OS Synchronization Mechanisms

1. *Mutual exclusion* locks
   - Serialize access to a shared resource
2. *Counting semaphores*
   - Synchronize execution
3. *Readers/writer* locks
   - Serialize access to resources whose contents are searched more than changed
4. *Condition variables*
   - Used to block until shared data changes state
5. *File locks*
   - System-wide readers/write locks access by filename

Additional ACE Synchronization Mechanism

1. *Guards*
   - An exception-safe scoped locking mechanism
2. *Barriers*
   - Allows threads to synchronize their completion
3. *Token*
   - Provides absolute scheduling order and simplifies multi-threaded event loop integration
4. *Task*
   - Provides higher-level "active object" semantics for concurrent applications
5. *Thread-specific storage*
   - Low-overhead, contention-free storage

Concurrency Mechanisms in ACE



Solaris Synchronization Primitives

- Each synchronization facility has a set of routines that operate on instances called *synchronization variables*
  - These variables may be allocated statically or dynamically
  - Variables must be allocated in memory that is globally accessible, *e.g.*,
    - . Allocated in global process memory and shared by multiple
    - ▷ Placed into shared memory or mapped files and accessed via separate processes
  - Depending on flags, different behavior may be selected during variable initialization

Solaris Synchronization Primitives (cont'd)

- All synchronization variables may be placed in shared memory and shared between threads running in multiple processes
  - *Intra-process* behavior vs. *inter-process* behavior is selected by using the USYNC_THREAD vs. USYNC_PROCESS flags at initialization time...
  - Note that memory-mapped files may be used to provide persistent locks that are shared between processes
  - If a variable is initialized to 0, the "default behavior" is selected
    - ▹ Default is local to one process (*i.e.*, USYNC_THREAD)
- Three methods for implementing locks are *spin locks*, *sleep locks*, and *adaptive locks*

Mutex Synchronization

- The simplest type of synchronization variable is the "mutex" (mutual exclusion) lock
- Only one thread at a time may "own" a mutex lock
  - *i.e.*, used to implement "critical sections"...
- Implemented to be highly efficient, but limited in functionality
  - *e.g.*, lock/unlock operations must be "fully-bracketed"

The Mutex API

- **int** mutex_init (mutex_t *mp, **int** type, **void** *arg);
- **int** mutex_destroy (mutex_t *mp);
- **int** mutex_lock (mutex_t *mp);
  - Acquire lock ownership (wait on priority queue if necessary)
- **int** mutex_trylock (mutex_t *mp);
  - Conditionally acquire lock (*i.e.*, don't wait on queue)
- **int** mutex_unlock (mutex_t *mp);
  - Release lock and unblock thread at head of priority queue, if necessary
  - Only the owner of a mutex may unlock it

Programming with Mutexes

- Simple resource example

```
static mutex_t count_mutex; // Initialized to 0
static int count;

int increment_count (void) {
        mutex_lock (&count_mutex);
        count = count + 1; /* atomic update */
        mutex_unlock (&count_mutex);
}

int get_count (void) {
        int c;
        mutex_lock (&count_mutex);
        c = count; /* ensure memory synchronization...*/
        mutex_unlock (&count_mutex);
        return c;
}
```

Condition Variables

- Used to "sleep/wait" until a particular condition involving shared data occurs
  - Conditions may be arbitrarily complex
- Allows more complex scheduling decisions, compared with simple mutex
  - *i.e.*, a mutex makes *other* threads wait, whereas a condition variable allows a thread to make *itself* wait for a particular condition involving shared data
  - Usually more efficient/correct than busy waiting...
- Are always used in conjunction with a mutex lock

Condition Variable API

- **int** cond_init (cond_t *cvp, **int** type, **int** arg);
- **int** cond_destroy (cond_t *cvp);
- **int** cond_wait (cond_t *cvp, mutex_t *mp);
  - Typically used in conjunction with a "condition expression"
  - Block until condition is signaled
  - Atomically release lock before blocking
  - Atomically reacquire lock before returning
    - ▷ Necessitates retesting condition...

Condition Variable API

- **int** cond_timedwait (cond_t *cvp, mutex_t *mp, timestruc_t *abstime);
  - Block on condition, or until absolute time-of-day has passed
- **int** cond_signal (cond_t *cvp);
  - Signal *one* thread blocked in `cond_wait`
  - If no thread is waiting, signal is ignored...
- **int** cond_broadcast (cond_t *cvp);
  - Signal *all* threads blocked in `cond_wait`
  - Use with care due to avoid the "thundering herd" problem...
  - Useful for allowing threads to contend for variable amounts of resources when resources are freed dynamically

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Condition Variable Patterns

- A particular idiom is typically associated with condition variables

```
// Global variables
static mutex_t m; // Initialized to 0
static cond_t c; // Initialized to 0
void some_function (void)
{
      mutex_lock (&m);
      while (condition expression is not true)
            cond_wait (&c, &m);
      /* Atomically modify shared information */
      mutex_unlock (&m);
      /* ...*/
}
```

- Warning!!!! Always make sure to invoke condition variable functions while holding the associated mutex lock!!!
  - Otherwise, "lost wakeup bugs" occur...

Condition Variable Patterns (cont'd)

- Another idiom is associated with releasing resources via condition variables

```
void release_resources (void)
{
      // Automatically acquire the lock.
      mutex_lock (&m);

      // Atomically modify shared information here...

      cond_signal (&c);
      // Could also use cond_broadcast().
      mutex_unlock (&m);
}
```

Programming with Condition Variables

- Implement general P and V using mutex and condition vars

```
static mutex_t count_lock; // Initialized to 0
static cond_t count_nonzero; // Initialized to 0
static unsigned int count; // Initialized to 0

void P (void) {
      mutex_lock (&count_lock);
      while (count == 0)
            cond_wait (&count_nonzero, &count_lock);
      count = count − 1;
      mutex_unlock (&count_lock);
}

void V (void) {
      mutex_lock (&count_lock);
      // Order of the following lines doesn't matter
      if (count == 0)
            cond_signal (&count_nonzero);
      count = count + 1;
      mutex_unlock (&count_lock);
}
```

Programming with Condition Variables (cont'd)

- Timed wait with a condition variable

```
const int TIMEOUT = 10;
static timestruc_t tm;
static mutex_t m;
static cond_t c;
// ...
tm.tv_sec = time (0) + timeout;
tm.tv_nsec = 0;
mutex_lock (&m);
while (/* cond == FALSE */) {
      int err = cond_timedwait (&c, &m, &tm);
      if (err == etime) {
            /* handle timeout */
            break;
      }
}
/* do work */
mutex_unlock (&m);
```

Programming with Condition Variables (cont'd)

- Illustration of cond_broadcast()

```
static mutex_t rsrc_lock; // Initialized to 0
static cond_t rsrc_add; // Initialized to 0
static unsigned int resources, waiting;

int obtain_resources (int amount) {
      mutex_lock (&rsrc_lock);
      while (resources < amount) {
            waiting++;
            cond_wait (&rsrc_add, &rsrc_lock);
      }
      resources -= amount;
      mutex_unlock (&rsrc_lock);
}

int release_resources (int amount) {
      mutex_lock (&rsrc_lock);
      resources += amount;
      if (waiting > 0) {
            waiting = 0;
            cond_broadcast (&rsrc_add);
      }
      mutex_unlock (&rsrc_lock);
}
```

Semaphores

- Semaphores are conceptually non-negative integers that may be incremented and decremented *atomically*
- They are less efficient than mutexes, but more general
  - *e.g.*, they need not be acquired and released by the same thread
    - ▹ *i.e.*, they may be used in signal handlers or other asynchronous event notification contexts
- It is not necessary to acquire a mutex lock to use a semaphore

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Semaphore API

- **int** sema_init (sema_t *sp, **unsigned int** count, **int** type, **void** *arg);
  - `count` gives initial value of semaphore
- **int** sema_destroy (sema_t *sp);
- **int** sema_wait (sema_t *sp);
  - Block the thread until the semaphore count becomes greater than 0, then decrement it
- **int** sema_trywait (sema_t *sp);
  - Decrement the semaphore if count is greater than 0, otherwise, return an error
- **int** sema_post (sema_t *sp);
  - Increment the semaphore, potentially unblocking a waiting thread

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Programming with Semaphores

- Simple producer/consumer semaphore example

```
static int rd_ptr = 0;
static int wr_ptr = 0;
static data_t buf[BUFSIZ];
static sema_t empty, full; // Initialized to 0

// ...
      sema_init (&empty, 1, 0, 0);

/* Producer thread 1 */
while (work_to_do) {
      buf[wr_ptr] = produce ();
      sema_wait (&empty);
      wr_ptr = (wr_ptr + 1) % BUFSIZ;
      sema_post (&full);
}

/* Consumer thread 2 */
while (work_to_do) {
      sema_wait (&full);
      consume (buf[rd_ptr]);
      sema_post (&empty);
      rd_ptr = (rd_ptr + 1) % BUFSIZ;
}
```

Readers/writer Locks

- Allow many threads simultaneous read-only access to a protected object
  - However, only a single thread may have write access to the object while excluding any readers or other writers
- Used to protect data that is read more often than written
- Must be fully bracketed (as with mutex)
- Preference is given to writers...

Readers/writer Lock API

- **int** rwlock_init (rwlock_t *rwlp, **int** type, **void** * arg);
- **int** rwlock_destroy (rwlock_t *rwlp);
- **int** rw_wrlock (rwlock_t *rwlp);
  - Acquires a write lock, but block if any readers or a writer hold the lock
- **int** rw_rdlock (rwlock_t *rwlp);
  - Acquire a read lock, but block if a writer holds the lock

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Readers/writer API (cont'd)

- **int** rw_unlock (rwlock_t *rwlp);
  - Unlock a read/write lock
- **int** rw_tryrdlock (rwlock_t *rwlp);
  - Conditionally acquire read lock
- **int** rw_trywrlock (rwlock_t *rwlp);
  - Conditionally acquire write lock

Programming with Readers/writer Locks

- Concurrent bank account program, supports multiple readers, but only 1 writer...

```
static rwlock_t account_lock; // Initialized to 0
static float checking_balance = 100.0;
static float saving_balance = 100.0;

float get_balance (void) {
        float bal;

        rw_rdlock (&account_lock);
        bal = checking_balance + saving_balance;
        rw_unlock (&account_lock);
        return val;
}

void transfer_checking_to_savings (float amount) {
        rw_wrlock (&account_lock);
        checking_balance = checking_balance − amount;
        savings_balance = savings_balance + amount;
        rw_unlock (&account_lock);
}
```

Comparison of Synchronization Primitives

- Mutex locks are the most basic and most efficient in terms of time and space
  - Based on adaptive spin-locks
- Condition variables provide a different flavor of locking than mutexes and semaphores

. *i.e.*, blocking themselves rather than blocking other

- They are *much* less efficient than mutexes since they use sleep locks

Comparison of Synchronization Primitives (cont'd)

- Semaphores use more memory than mutexes and condition variables
  - Unlike mutexes, they do not require that the original thread is also the thread to release the semaphore
    - ▷ They also allow more general "counting" behavior, as opposed to binary behavior
  - Unlike condition variables they function only on count state, rather than complex condition state
- Readers/writer locks are the most complex synchronization mechanism
  - Use at a fairly coarse-grained level

Multi-threaded Signal Handling

- Signal handling in a single-threaded process is different than in a multi-threaded process
- For example, in a single-threaded process there is never any question as to which "thread" handles a signal
- Likewise, the use of reliable signal mechanisms enable critical sections without explicit locking
- These issues become problematic with in multi-threaded processes...

Two Categories of Signals

1. *Traps* (*e.g.*, SIGSEGV, SIGPIPE)
   - Result from execution of a specific thread and are handled only by the thread that caused them
   - May be generated and handled simultaneously
2. *Interrupts* (*e.g.*, SIGINT, SIGIO)
   - Are asynchronous to any thread, resulting from some external action
   - May be handled by any thread whose signal mask is enabled
   - Only one thread is chosen if several are capable of handling the signal
   - If all threads mask the signal it remains pending until some thread enables it

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Advanced Topics

- The scope of `setjmp` and `longjmp` is limited to one thread
  - In particular, this means that a thread that handles a signal can only perform a **`longjmp`** if the corresponding **`setjmp`** was performed in the same thread
- The following thread-related functions are async-safe, and may be called in the context of a signal handler

1. **`sema_post`**
2. **`thr_sigsetmask`**
3. **`thr_kill`**

Signal Masks

- Each thread has its own signal mask
  - Therefore, a thread may block signals selectively
  - Note that all threads in a process share the same set of signal handlers...
    - ▷ Per-thread signal handlers must be programmed explicitly by developers
- Threads can send signals to other threads in their process via `thr_kill`
  - This signal behaves as a trap...
  - Note, there is no direct way to send a signal to specific thread in a different process

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Programming with Signal Masks

- The `thr_sigsetmask` function sets the thread's signal mask (which is initially inherited from the parent thread)
  - **int** thr_sigsetmask (**int** how, **const** sigset_t *set, sigset_t *oset);
- This example shows how to create a default thread with a new signal mask

```
thread_t tid;
sigset_t new_mask, orig_mask;
int error;

sigfillset (&new_mask);
sigdelset (&new_mask, SIGINT);
thr_sigsetmask (SIG_SETMASK, &new_mask, &orig_mask):
error = thr_create (0, 0, do_func, 0, 0, &tid);
thr_sigsetmask (SIG_SETMASK, &orig_mask, 0);
```

Waiting and Signaling Threads

- The `thr_kill` function sends the specified signal to a specific thread
  - **int** thr_kill (thread_t target_thread, **int** sig);
- The `sigwait` function waits for a pending signal from the set specified by its argument (regardless of the process signal mask)
  - **int** sigwait (sigset_t *set);
  - `sigwait` returns the number of the pending signal
  - This function is typically used to wait for signals in a separate thread, rather than using a signal handler

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Programming with sigwait()

- Example illustrating the use of `sigwait`

```
static mutex_t m; // Initialized to default
static int hup = 0;

int main (void) {
      thread_t t;
      int finishup = 0;
      sigset_t set;
      ...
      sigfillset (&set); /* block all signals */
      thr_sigsetmask (SIG_BLOCK, &set, 0);
      thr_create (0, 0, wait_hup, 0, THR_DETACHED, &t);
      do {
            /* do processing */
            mutex_lock (&m);
            if (hup)
                  finishup = 1;
            mutex_unlock (&m);
      } while (finishup == 0);
}

void *wait_hup (void *) {
      sigset_t set;
      sigemptyset (&set);
      sigaddset (&set, SIGHUP);
      sigwait (&set);
      mutex_lock (&m);
      hup = 1;
      mutex_unlock (&m);
}
```

Process Creation and Destruction

- When a process containing multiple threads *forks*, it creates an exact duplicate
  - *i.e.*, all threads are duplicated
    - ▹ However, all interruptible system calls in other threads return EINTR
- A new system call `fork1()` may be used to duplicate the address space, but only duplicate the invoking thread
  - Typically used to save time, especially if an `exec` is performed immediately following the `fork1`

Hazards of Using fork() and vfork()

- There are a number of hazards associated with using `fork1` and `vfork`
  - If the parent process had threads holding locks then the child process contains locks held by non-existent threads
    - ▹ This may lead to deadlock
  - Before calling `exec`, do not call library functions that use a lock held by more than one thread
  - Do not create new threads between calls to `vfork` and `exec`

Thread-Specific Data

- Thread-specific data is maintained on a per-thread basis
  - It is the only way to define and refer to data that is private to a thread
- Each thread-specific data item is associated with a key that is global to all threads in a process
  - Using the key, a thread can access a void * pointer that is maintained per-thread
    - ▹ This pointer generally points to data allocated off the global heap

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Thread-Specific Data API

- int thr_keycreate (thread_key_t *, void (*)(void *value));
  - Allocates a global key value
  - The second parameter is a pointer-to-function that is called to cleanup the allocated memory when the thread exits
- int thr_setspecific (thread_key_t, void *value);
  - Binds a value to the key for the calling thread
- int thr_getspecific (thread_key_t, void **value);
  - Retrieves the current value bound to the key for the calling thread

Programming with Thread-Specific Data

- Example of thread-specific data: Trace class

```
class Trace
{
public:
  Trace (void);
  Trace (char *n, int line = 0, char *file = "");
  ~Trace (void);

  static void start_tracing (void) { enable_tracing_ = 1; }
  static void stop_tracing (void) { enable_tracing_ = 0; }
  static void set_nesting_indent (int indent);

private:
  static thread_key_t depth_key_; //
  static thread_key_t indent_key_;
  static int       once_;
  static Trace       t_;

  static void       cleanup (void *);
  static int       *___nesting_indent();
  static int       *___nesting_depth();
#define nesting_indent_ (*(___nesting_indent()))
#define nesting_depth_ (*(___nesting_depth()))
  static int enable_tracing_;

  char *name_;
  enum {DEFAULT_DEPTH = 0, DEFAULT_INDENT = 3, DEFAULT_TRACING = 0};
};
```

Thread-Specific Data (cont'd)

- Example of thread-specific data: Trace class

```
void
Trace::set_nesting_indent (int indent)
{
  nesting_indent_ = indent; // Access thread-specific data
}

Trace::Trace (char *n, int line, char *file)
{
  if (Trace::enable_tracing_)
    Log_Msg::log (LOG_INFO, "%*s(%t) calling %s, file ‘%s’, line %d\n",
                  nesting_indent_ * nesting_depth_++, // Access TSD
                  "", this->name_ = n, file, line);
}

Trace::~Trace (void)
{
  if (Trace::enable_tracing_)
    Log_Msg::log (LOG_INFO, "%*s(%t) leaving %s\n",
                  nesting_indent_ * --nesting_depth_, // Access TSD
                  "", this->name_);
}
```

Thread-Specific Data (cont'd)

- Example of thread-specific data: Trace class

```
Trace::Trace (void)
{
  if (Trace::once_ == 0)
    {
      this->name_ = "static dummy";
      Trace::once_ = 1;
      thr_keycreate (&Trace::depth_key_, Trace::cleanup);
      thr_keycreate (&Trace::indent_key_, Trace::cleanup);
    }
}

void
Trace::cleanup (void *ptr)
{
  Trace::stop_tracing ();
  delete ptr;
}
```

Thread-Specific Data (cont'd)

- Example of thread-specific data: Trace class

```
int *
Trace::___nesting_depth (void)
{
  int *ip;

  thr_getspecific (Trace::depth_key_, (void **) &ip);
  if (ip == 0) // First time in
    {
      ip = new int (Trace::DEFAULT_DEPTH);
      thr_setspecific (Trace::depth_key_, (void *) ip);
    }
  return ip;
}

int *
Trace::___nesting_indent (void)
{
  int *ip = 0;

  thr_getspecific (Trace::indent_key_, (void **) &ip);
  if (ip == 0) // First time in
    {
      ip = new int (Trace::DEFAULT_NESTING);
      thr_setspecific (Trace::indent_key_, (void *) ip);
    }
  return ip;
}
```

Example: File Copy

- Perform simultaneous I/O on two different devices

```
#define _REENTRANT
#include <stdio.h>
#include <thread.h>
#include <synch.h>

sema_t emptybuf_sem, fullbuf_sem;

struct {
  char data[BUFSIZ]; int size;
} buf[2];

void *producer (void *), *consumer (void *);

int main (int argc, char *argv[])
{
  thread_t r_id, w_id, id;
  if (sema_init (&emptybuf_sem, 2, 0, 0) != 0 ||
      sema_init (&fullbuf_sem, 0, 0, 0) != 0)
    return 1;
  if (thr_create (0, 0, producer, 0, THR_NEW_LWP, &r_id) == 0
      && thr_create (0, 0, consumer, 0, THR_NEW_LWP, &w_id) == 0) {
    int status;
    while (thr_join (0, &id, (void **) &status) == 0)
      fprintf (stderr, "waited id = %d, status = %d\n", id, status);
    return 0;
  }
  return 1;
}
```

Example: File Copy (cont'd)

- Producer thread

```
void *producer (void *x)
{
  int i = 0;

  for (;;) {
    sema_wait (&emptybuf_sem);
    buf[i].size = read (0, buf[i].data, sizeof buf[i].data);
    sema_post (&fullbuf_sem);
    if (buf[i].size <= 0)
      return (void *) 0;
    i = 1 - i;
  }
}
```

Example: File Copy (cont'd)

- Consumer thread

```
void *consumer (void *x)
{
  int i = 0;
  for (;;) {
    sema_wait (&fullbuf_sem);
    if (buf[i].size <= 0)
      return (void *) 0;
    if (write (1, buf[i].data, buf[i].size) != buf[i].size) {
      fprintf (stderr, "write failed\n");
      return (void *) -1;
    }
    sema_post (&emptybuf_sem);
    i = 1 - i;
  }
}
```

Example: Matrix Multiplication

- This example illustrates conditional variables and mutexes in the context of multiplication of two-dimensional matrices

```
#define _REENTRANT
#include <stdio.h>
#include <thread.h>
#include <synch.h>

#define SZ 10
#define NCPU 4
int number_of_cpus = NCPU;

typedef int (*MATRIX_P)[SZ];
typedef int MATRIX[SZ][SZ];

static MATRIX m1 =
{
  1, 2, 3, 4, 5, 6, 7, 8, 9, 10,
  1, 2, 3, 4, 5, 6, 7, 8, 9, 10,
  1, 2, 3, 4, 5, 6, 7, 8, 9, 10,
  1, 2, 3, 4, 5, 6, 7, 8, 9, 10,
  1, 2, 3, 4, 5, 6, 7, 8, 9, 10,
  1, 2, 3, 4, 5, 6, 7, 8, 9, 10,
  1, 2, 3, 4, 5, 6, 7, 8, 9, 10,
  1, 2, 3, 4, 5, 6, 7, 8, 9, 10,
  1, 2, 3, 4, 5, 6, 7, 8, 9, 10,
  1, 2, 3, 4, 5, 6, 7, 8, 9, 10,
};
```

```
static MATRIX m2 =
{
  10, 9, 8, 7, 6, 5, 4, 3, 2, 1,
  10, 9, 8, 7, 6, 5, 4, 3, 2, 1,
  10, 9, 8, 7, 6, 5, 4, 3, 2, 1,
  10, 9, 8, 7, 6, 5, 4, 3, 2, 1,
  10, 9, 8, 7, 6, 5, 4, 3, 2, 1,
  10, 9, 8, 7, 6, 5, 4, 3, 2, 1,
  10, 9, 8, 7, 6, 5, 4, 3, 2, 1,
  10, 9, 8, 7, 6, 5, 4, 3, 2, 1,
  10, 9, 8, 7, 6, 5, 4, 3, 2, 1,
  10, 9, 8, 7, 6, 5, 4, 3, 2, 1,
};

static MATRIX m3;

struct
{
  /* Matrix data */
  MATRIX_P m1;
  MATRIX_P m2;
  MATRIX_P m3;
  int row;
  int col;

  /* Multi-processing control variables */
  mutex_t lock;
  cond_t start_cond;
  cond_t done_cond;

  /* More control variables */
  int todo;
  int notdone;
  int workers;
} work;

mutex_t mul_lock;
```

```
static void
print (MATRIX m)
{
  int i, j;

  for (i = 0; i < SZ; i++)
    {
      for (j = 0; j < SZ; j++)
        printf ("%4d", m[i][j]);

      printf ("\n");
    }
}

static void *
worker (void *)
{
  MATRIX_P m1, m2, m3;
  int row;
  int col;
  int i;
  int result;

  for (;;)
    {
      mutex_lock (&work.lock);

      while (work.todo == 0)
        cond_wait (&work.start_cond, &work.lock);

      work.todo--;
      m1 = work.m1;
      m2 = work.m2;
      m3 = work.m3;
      row = work.row;
      col = work.col;
```

```
      if (++work.col == SZ)
        {
          work.col = 0;
          if (++work.row == SZ)
            work.row = 0;
        }

      mutex_unlock (&work.lock);

      result = 0;

      for (i = 0; i < SZ; i++)
        result += m1[row][i] * m2[i][col];

      m3[row][col] = result;

      mutex_lock (&work.lock);
      work.notdone--;

      if (work.notdone == 0)
        cond_signal (&work.done_cond);
      mutex_unlock (&work.lock);
    }
  return 0;
}

static void
matrix_multiply (MATRIX m1, MATRIX m2, MATRIX m3)
{
  int i;

  mutex_lock (&mul_lock);
  mutex_lock (&work.lock);

  if (work.workers == 0)
    {
```

```
      thread_t t_id;

      for (i = 0; i < number_of_cpus; i++)
        thr_create (0, 0, worker, 0,
                    THR_NEW_LWP | THR_DETACHED, &t_id);

      work.workers = number_of_cpus;
    }

  work.m1 = m1;
  work.m2 = m2;
  work.m3 = m3;
  work.row = 0;
  work.col = 0;
  work.todo = SZ * SZ;
  work.notdone = SZ * SZ;
  cond_broadcast (&work.start_cond);

  while (work.notdone)
    cond_wait (&work.done_cond, &work.lock);

  mutex_unlock (&work.lock);
  mutex_unlock (&mul_lock);
}

int
main (int argc, char *argv)
{
  int i;

  print (m3);

  for (i = 0; i < 10; i++)
    matrix_multiply (m1, m2, m3);
  print (m3);
}
```

Conclusions and Caveats

- Some applications do not benefit directly from threads
  - *e.g.*, CPU-bound programs on a uni-processor
- Threads should be created for processing that lasts at least several thousand machine instructions
- Synchronization may be expensive
  - Therefore, choose primitives carefully
- Developer intuition is often underdeveloped...
- Debugging is more complicated
  - *e.g.*, lack of tools