Synchronization II

To do …

- Condition Variables
- Semaphores and monitors
- Some classical problems
- Next time: Deadlocks

Condition variables

- Many times a thread wants to check whether a condition is true before continuing execution
  - A parent waiting on a child, a consumer waiting on something to consume, …
  - *But spinning on a shared variable is inefficient*

- Condition variables
  - An explicit queue where threads can go when some state is not what they want (*waiting* on a change)
  - Until some other thread changes the state and informs them of it, *signaling* on the condition

```
pthread_cond_t c;
pthread_cond_wait(pthread_cond_t *c, pthread_mutex_t *m);
pthread_cond_signal(pthraed_cond_t *c);
```

Waiting on your child

- Before we move on, did you notice?

```
pthread_cond_wait(pthread_cond_t *c, pthread_mutex_t *m);
```

  - Assumes mutex is locked before wait is called
    - Wait must release it and put the thread to sleep, *atomically*
    - When the thread wakes up, re-acquires the lock before returning
  - All to prevent race condition when a thread is trying to put itself to sleep

Waiting on your child

- Back to parent and child

```
int done = 0;
pthread_mutex_t m = PTHREAD_MUTEX_INITIALIZER;
pthread_cond_t c = PTHREAD_COND_INITIALIZER;

int main(int argc, char *argv[]) {
   pthread_t p;
   printf("parent: begin\n");
   pthread_create(&p, NULL, child, NULL);
   thr_join();
   printf("parent: done\n");
   return 0;
}
```

```
void thr_join() {
   pthread_mutex_lock(&m);
   while (done == 0)
      pthread_cond_wait(&c, &m);
   pthread_mutex_unlock(&m);
}
```

```
void *child(void *arg) {
   printf("child\n");
   thr_exit();
   return 0;
}
```

```
void thr_exit() {
   pthread_mutex_lock(&m);
   done = 1;
   pthread_cond_signal(&c);
   pthread_mutex_unlock(&m);
}
```

Waiting on your child

```
void thr_join() {
   pthread_mutex_lock(&m);
   while (done == 0)
      pthread_cond_wait(&c, &m);
   pthread_mutex_unlock(&m);
}
```

That `while` *doesn't seem strictly necessary, wouldn't an* `if` *do …* wait a bit

```
void thr_exit() {
   pthread_mutex_lock(&m);
   done = 1;
   pthread_cond_signal(&c);
   pthread_mutex_unlock(&m);
}
```

- Two cases to consider
  - Parent creates the child and continue running
    - Gets the lock, check if done and put itself to sleep
    - Child runs, gets the lock, sets done and signals the parent
    - Parent returns from wait with lock held, unlocks it and is done
  - If child runs first, sets done, signals (nobody is waiting) and returns; parent check child is done and returns

Non-working approaches

```
void thr_exit() {
   pthread_mutex_lock(&m);
   /* done = 1; */
   pthread_cond_signal(&c);
   pthread_mutex_unlock(&m);
}

void thr_join() {
   pthread_mutex_lock(&m);
   /* while (done == 0) */
   pthread_cond_wait(&c, &m);
   pthread_mutex_unlock(&m)
}
```

Do you need `done`*?*

- If the child runs immediately, the signal will be lost
- Parent will call wait (there's nothing to check) and go to sleep for ever

```
void thr_exit() {
   done = 1;
   pthread_cond_signal(&c);
}

void thr_join() {
   if (done == 0)
       pthread_cond_wait(&c);
}
```

Do you need that `mutex`*?*

- What would happen if the parent is interrupted after checking 'done' but before going to sleep on wait?
- Child runs, signals nobody (parent is not there yet!) and ..
- When parent continues it goes to sleep, *for ever!*

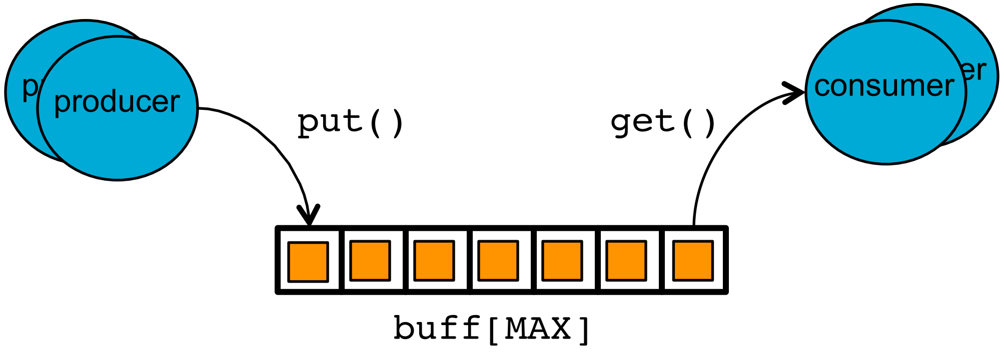
Producer/consumer problem

- Producer-consumer problem, aka bounded buffer
  - Two or more processes & one shared, fixed-size buffer
  - Some put data times into a buffer, others takes them out
  - E.g., Web server with producers taken orders and consumer threads processing them

```
int buff[MAX];
int fill = 0;
int use = 0;
int count = 0;

void put(int value) {
   buff[fill] = value;
   fill = (fill + 1) % MAX;
   count++;
}

int get() {
   int tmp = buffer[use];
   use = (use + 1) % MAX;
   count--;
   return tmp;
}
```



Producer/consumer problem

- "Simple solution"
  - If buffer empty, producer goes to sleep to be awaken when the consumer has removed one or more items
  - Similarly for the consumer
  - (a first try)

```
cond_t cond;
mutex_t mutex;

void *producer(void *arg) {
   int i;
   for (i = 0; i < loops; i++) {
      pthraed_mutex_lock(&mutex);
      if (count == MAX)
         pthread_cond_wait(&cond, &mutex);
      put(i);
      pthread_cond_signal(&cond);
      pthread_mutex_unlock(&mutex);
   }
}
```

```
void *consumer(void *arg) {
   int i;
   for (i = 0; i < loops; i++) {
      pthraed_mutex_lock(&mutex);
      if (count == 0)
         pthread_cond_wait(&cond, &mutex);
      int tmp = get(i);
      pthread_cond_signal(&cond);
      pthread_mutex_unlock(&mutex);
   }
}
```

A while for an if

```
cond_t cond;
mutex_t mutex;

void *producer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        pthraed_mutex_lock(&mutex);
        if (count == MAX)
            pthread_cond_wait(&cond, &mutex);
        put(i);
        pthread_cond_signal(&cond);
        pthread_mutex_unlock(&mutex);
    }
}
void *consumer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        pthraed_mutex_lock(&mutex);
        if (count == 0)
            pthread_cond_wait(&cond, &mutex);
        int tmp = get(i);
        pthread_cond_signal(&cond);
        pthread_mutex_unlock(&mutex);
    }
}
```

2 consumers/1 producer

- Consumer 1 tries to get item but finds buffer empty, and waits
- Producer puts an item and signals this, moving C1 to ready queue
- Consumer 2 sneaks in and gets the one item
- Now C1 runs; just before returning from the wait it re-acquires the lock, returns and calls get to find an empty buffer!!

With condition variables, always use while loops

One condition variable is not enough

```
cond_t cond;
mutex_t mutex;

void *producer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        pthraed_mutex_lock(&mutex);
        while (count == MAX)
            pthread_cond_wait(&cond, &mutex);
        put(i);
        pthread_cond_signal(&cond);
        pthread_mutex_unlock(&mutex);
    }
}

void *consumer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        pthraed_mutex_lock(&mutex);
        while (count == 0)
            pthread_cond_wait(&cond, &mutex);
        int tmp = get(i);
        pthread_cond_signal(&cond);
        pthread_mutex_unlock(&mutex);
    }
}
```

2 consumers/1 producer and lets MAX = 1

- Both consumers try to get the item, find buffer empty and go to sleep
- Producer puts item, wakes up a consumer (1) and goes to sleep
- Consumer comes along and gets the one item and signals …
- *but who!?* Both producer and Consumer 2 are sleeping

Finally a solution

```
cond_t empty, fill;
mutex_t mutex;

void *producer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        pthraed_mutex_lock(&mutex);
        while (count == MAX)
            pthread_cond_wait(&empty, &mutex);
        put(i);
        pthread_cond_signal(&fill);
        pthread_mutex_unlock(&mutex);
    }
}
```

Simple solution – two condition variables

Producer waits on "empty" and signals "fill"

```
void *consumer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        pthraed_mutex_lock(&mutex);
        while (count == 0)
            pthread_cond_wait(&fill, &mutex);
        int tmp = get(i);
        pthread_cond_signal(&empty);
        pthread_mutex_unlock(&mutex);
    }
}
```

Consumers do the opposite – wait on "fill" and signal "empty"

Semaphores

- A synchronization primitive
- Higher level of abstraction than locks, also replacing condition variables
- Invented by Dijkstra in '68 as part of THE OS
- Atomically manipulated by two operations

```
sem_wait(sem_t *sem)
sem_post(sem_t *sem)
```

`sem_wait(sem_t *sem)` / P / down(sem)
`sem_post(sem_t *sem)` / V / up(sem)

  - The initial value determine its behavior, so it must be first initialized

```
sem_init(sem_t *sem, int pshared, unsigned int value);
```

Ignored this for now, but basically shared by al threads of a process (0) or by processes through shared memory (!=0)

Blocking in semaphores

- Each semaphore has an associated queue of processes/threads
  - sem_wait / P
    - Decrement the value of the semaphore by 1
    - If sem was “unavailable” (non-positive), wait on the queue
  - P – not really for *proberen* or *passeer* but for a made-up word *prolaag* – *“try to reduce”*

```
int sem_wait(sem_t *s){
  s.value--;
  wait in a queue of s until (s.value > 0);
}
```

Atomic action

Semaphores

- …
  - sem_post / V
    - Increment the value of the semaphore by one
    - If thread(s) are waiting on the queue, unblock one
  - V – *verhogen* – increase in Dutch

```
int sem_post(sem_t *s) {
  s.value++;
  if there are 1+ threads waiting
    wake one thread up;
}
```

Atomic action

Binary semaphores - locks

```
sem_t m;
sem_init(&m, 0, 1);

sem_wait(&m);
/* critical section */
sem_post(&m);
```

Why 1? Look at the definition of wait and post

```
int sem_wait(sem_t *s){
  s.value--;
  wait in a queue of s until (s.value > 0);
}

int sem_post(sem_t *s) {
  s.value++;
  if there are 1+ threads waiting
    wake one thread up;
}
```

So, if m = 1 the first thread will go in and decrement its value, the following thread will wait … until the thread inside increments it within `sem_post()`

Semaphores as condition variables

- Waiting on a condition, as when parent waits for child to terminate

```
sem_t s;

void *child(void *arg) {
  printf("child\n");
  sem_post(&s);
  return NULL;
}

int main(int argc, char*argv[]) {
   sem_init(&s, 0, 0);
   printf("parent: begin\n");
   pthread_t c;
   pthread_create(c, NULL, child, NULL);
   sem_wait(&s);
   printf("parent: end\n");
   return 0;
}
```

Why 0?

So, if m = 0 and parent runs, will wait until the child runs and sets value to 1; If child runs first, the value will be 1 and the parent will go on without waiting

Semaphores – Producer/consumer v1

```
sem_t empty;
sem_t full;
sem_t mutex;

void *producer(void *arg) {
     int i;
     for (i = 0; i < loops; i++) {
       sem_wait(&empty);
       put(i);
       sem_post(&full);
    }
}

void *consumer(void *arg) {
     int i;
     for (i = 0; i < loops; i++) {
       sem_wait(&full);
       int tmp = get();
       sem_post(&empty);
    }
}

int main …
  ...
  sem_init(&empty, 0, MAX); /* MAX buffers are empty ... */
  sem_init(&full, 0, 0);    /* and 0 are full */
  ...
```

Yeap, those are CSs

```
void put(int value) {
   buff[fill] = value;
   fill = (fill + 1) % MAX;
}

int get() {
   int tmp = buffer[use];
   use = (use + 1) & MAX;
   return tmp;
}
```

Semaphores – Producer/consumer

```
sem_t empty;
sem_t full;
sem_t mutex;

void *producer(void *arg) {
     int i;
     for (i = 0; i < loops; i++) {
       sem_wait(&empty);
       sem_wait(&mutex);
       put(i);
       sem_post(&mutex);
       sem_post(&full);
    }
}

void *consumer(void *arg) {
     int i;
     for (i = 0; i < loops; i++) {
       sem_wait(&full);
       sem_wait(&mutex);
       int tmp = get();
       sem_post(&mutex);
       sem_post(&empty);
    }
}

int main …
  ...
  sem_init(&empty, 0, MAX); /* MAX buffers are empty ... */
  sem_init(&full, 0, 0);    /* and 0 are full */
  sem_init(&mutex, 0, 1);   /* set to 1, it's a lock */
  ...
```

Protect the critical section

Protect the critical section

Readers-writers problem

- The need for a more flexible type of lock, imagine a database or a simple linked list
  - Not problem with multiple readers allowed at once
  - Only one writer allowed at a time
    - If writers is in, nobody else is

```
typedef struct _rwlock_t {
    sem_t lock;
    sem_t writelock;
    int readers;
} rwlock_t;

void rwlock_acquire_writelock(rwlock_t *rw) {
    sem_wait(&rw->writelock);
}

void rwlock_release_writelock(rwlock_t *rw) {
    sem_post(&rw->writelock);
}
```

Simple, only a single writer allowed

First reader blocks the writer from entering

```
void rwlock_acquire_readlock(rwlock_t *rw) {
    sem_wait(&rw->lock);
    rw->readers++;
    if (rw->readers == 1)
      sem_wait(&rw->writelock);
    sem_post(&rw->lock);
}

void rwlock_release_readlock(rwlock_t *rw) {
    sem_wait(&rw->lock);
    rw->readers--;
    if (rw->readers == 0)
      sem_post(&rw->writelock);
    sem_post(&rw->lock);
}
```

Last reader lets the writer in

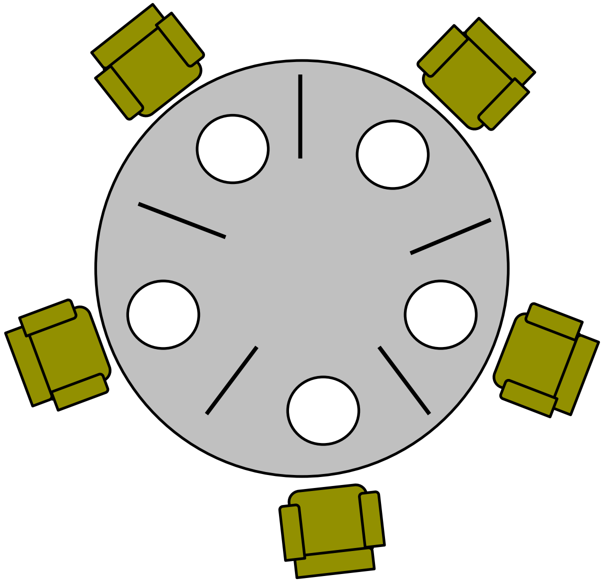
Dining philosophers

- Another one by Dijkstra
- Philosophers eat/think
  - To eat, a philosopher needs 2 chopsticks
  - Picks one at a time
- *How to prevent deadlock and starvation*

```
#define N 5

void philosopher(int i)
{
    while (TRUE) {
        think();
        take_chopstick(i);
        take_chopstick((i+1)%N);
        eat();
        put_chopstick(i);
        put_chopstick((i+1)%N);
    }
}
```

Now: Everybody takes the left chopstick!



Nonsolution

Why not just protect all this with a mutex?

Dining philosophers example

```
state[] – too keep track of philosopher's        state
(eating, thinking, hungry)
s[] – array of semaphores, one per philosopher
```

```
void philosopher(int i) {
  while(TRUE) {
    think();
    take_chopstick(i);
    eat();
    put_chopstick(i);
  }
}

void take_chopstick(int i) {
   sem_wait(&mutex);
   state[i] = HUNGRY;
   test(i);
   sem_post(&mutex);
   sem_wait(&s[i]);
}
```

```
void put_chopstick(int i) {
  sem_wait(&mutex);
  state[i] = THINKING;
  test(LEFT);
  test(RIGHT);
  sem_post(&mutex);
}

void test(int i) {
  if ((state[i] == hungry &&
     state[LEFT] != eating &&
     state[RIGHT] != eating) {
     state[i] = EATING;
     sem_post(&s[i]);
  }
}
```

Semaphores and deadlocks

- Semaphores solves most synchronization problems
  - But no control or guarantee of proper usage

Minor change?

```
void *consumer(void *arg) {
   int i;
   for (i = 0; i < loops; i++) {
     sem_wait(&full);
     sem_wait(&mutex);
     int tmp = get();
     sem_post(&mutex);
     sem_post(&empty);
   }
}

void *producer(void *arg) {
   int i;
   for (i = 0; i < loops; i++) {
     sem_wait(&empty);
     sem_wait(&mutex);
     put(i);
     sem_post(&mutex);
     sem_post(&full);
   }
}
```

```
void *consumer(void *arg) {
   int i;
   for (i = 0; i < loops; i++) {
     sem_wait(&mutex);
     sem_wait(&full);
     int tmp = get();
     sem_post(&empty);
     sem_post(&mutex);
   }
}

void *producer(void *arg) {
   int i;
   for (i = 0; i < loops; i++) {
     sem_wait(&mutex);
     sem_wait(&empty);
     put(i);
     sem_post(&full);
     sem_post(&mutex);
   }
}
```

Watch for deadlocks

- Deadlock!
  - Consumer holds the mutex and goes to sleep, to wait for the producer to put something
  - Producer can't put anything because consumer holds the lock!

```
void *consumer(void *arg) {
   int i;
   for (i = 0; i < loops; i++) {
     sem_wait(&mutex);
     sem_wait(&full);
     int tmp = get();
     sem_post(&empty);
     sem_post(&mutex);
    }
}
```

```
void *producer(void *arg) {
   int i;
   for (i = 0; i < loops; i++) {
     sem_wait(&mutex);
     sem_wait(&empty);
     put(i);
     sem_post(&full);
     sem_post(&mutex);
   }
}
```

Issues with semaphores

- Solves most synchronization problems, but:
  - We have seen, no control over their use, no guarantee of proper usage (our deadlock example)
  - Semaphores are essentially shared global variables
    - Can be accessed from anywhere (bad software engineering)
  - No connection between the semaphore & the data controlled by it
  - Used for both critical sections & for coordination (scheduling)

Monitors

- Higher level synchronization primitive – Monitors
  - A programming language construct
    - Set of procedures, variables and data structures
  - Monitor's internal data structures are private
- Monitors and mutual exclusion
  - Only one process active at a time
- To enforce sequences of events – Condition variables
  - Only accessed from within the monitor
  - Three operations – `wait`, `signal` & `broadcast`

Monitors

- `Wait`
  - Atomically releases the lock
  - Suspends execution of the calling thread, places it in the waiting queue
  - When the calling thread is re-enable, it requires the lock before returning from the wait
- A thread that waits “steps outside” the monitor (to the associated wait queue)
- A condition variable is memoryless, it has no internal state (the shared object defines its own); so, `wait` is not a counter – signal may get lost

Monitors

- `Signal`
  - Takes a waiting thread off the condition variable's waiting queue and marks it as eligible to run
- `Broadcast`
  - Like signal but for all threads waiting
- What happen after the signal?
  - Hoare – process awakened run
  - Brinch Hansen – process signaling must exit
  - *Mesa – process signaling continues to run*
- As a programmer – always check the condition after being woken! i.e., call within a **`while`**

```
while (predicateOnStateVar(…)) wait(&lock);
```

Producer/consumer

```
Monitor ProdCons {
  condition full, empty;
  int count;

  void insert(int item) {
    if (count == N) wait(full);
    insert_item(item);
    count++;
    if (count == 1) signal(full)
  }

  int remove(void) {
    if count == 0 wait(empty);
    return remove_item;
    count--;
    if (count == N – 1)
       signal(full);
  }
  count := 0;
}
```

```
void producer() {
   while TRUE {
     item = produce_item;
     ProdCons.insert(item);
   }
}

void consumer() {
   while TRUE {
     item = ProdCons.remove;
     consume_item(item);
   }
}
```

Monitors

- Monitors and mutual exclusion
  - Only one process active at a time – *how?*
  - Synchronization code is added by the compiler (or the programmer using locks)

- Clear similarities between the two – you can use one to implement the other

Monitors and semaphores

- A semaphore implemented as a monitor

```
Monitor class Semaphore {
  int s;
  Semaphore(int value) {
     s = value;
  }
  void wait() {
    while (s <= 0)
       wait();
    s--;
  }
  void post() {
     s++;
     signal();
  }
}
```

Using it as a binary semaphore

```
Semaphore s(1);

s.wait();
/* Critical section */
s.post();
```

Monitors

- Monitors - higher level synchronization primitive
  - A programming language construct
    - Collection of procedures, variables and data structures
  - Monitor’s internal data structures are private
- Monitors and mutual exclusion
  - Only one process active at a time
  - Synchronization code is added by the compiler (or the programmer using locks)
- To enforce sequences of events – Condition variables
  - Only accessed from within the monitor
  - Three operations – wait, signal & broadcast

Coming up

- Deadlocks

  How deadlock arise and what you can do about them