barriers (finish) / deadlock

last time

race conditions

- inconsistent results due to timing variation
- example: "lose" update due to reading value while update being computed

compilers, processors and memory access reordering

- order you write in C code [or even assembly] might not be order of accesses
- need special operations that gaurentee consistent order

locks for taking turns

- one thread can "hold" lock at a time
- lock operation waits for lock to be available (unlock'd)
- requires threads agree to get lock before using shared thing

barriers — advance threads in lock-step

exercise

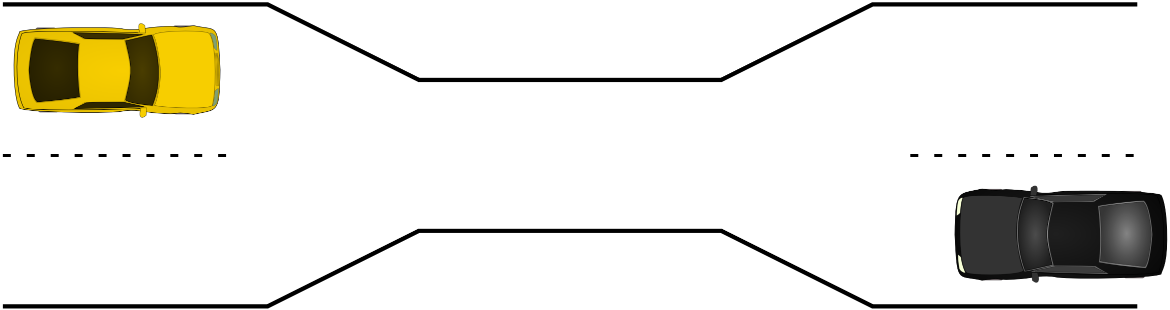
pthread_barrier_init ()

main ()
barrier_init (2)
thread_one
thread_two

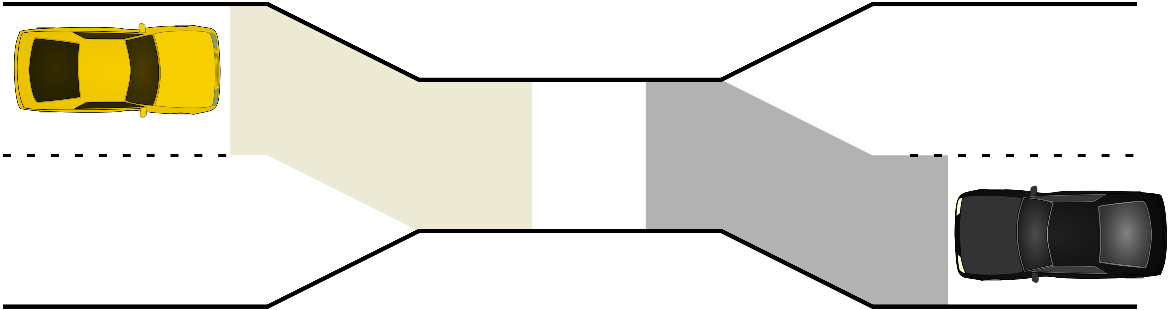
```
pthread_barrier_t barrier; int x = 0, y = 0;
void thread_one() {
    y = 10;
    pthread_barrier_wait(&barrier);     1
    y = x + y;        y = 30
    pthread_barrier_wait(&barrier);     2
    pthread_barrier_wait(&barrier);     3
    printf("%d %d\n", x, y);
                     50  30        after 3rd barrier
}
void thread_two() {
    x = 20;
    pthread_barrier_wait(&barrier);     1
    pthread_barrier_wait(&barrier);     2
    x = x + y;   x = 20+30 = 50
    pthread_barrier_wait(&barrier);     3
}
```

output? (if both run at once, barrier set for 2 threads)

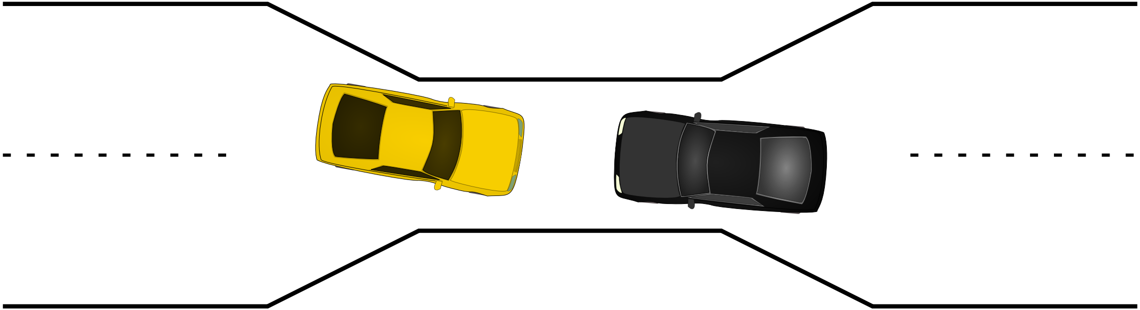
the one-way bridge



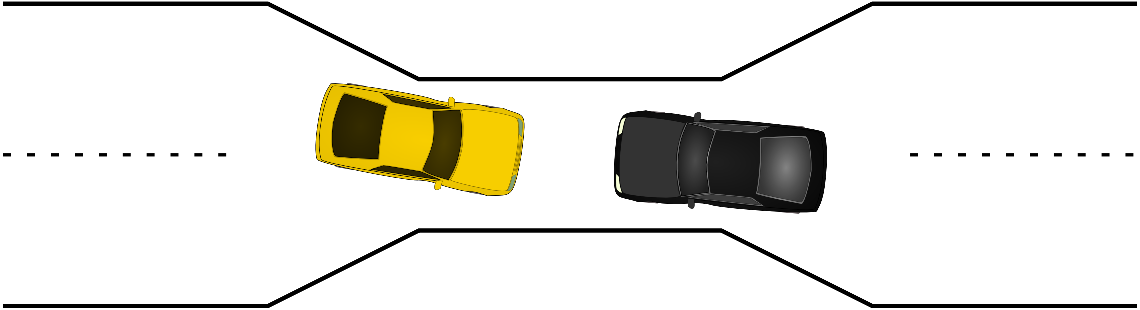
the one-way bridge



the one-way bridge



the one-way bridge



moving two files

```
struct Dir {
  mutex_t lock; HashMap entries;
};
void MoveFile(Dir *from_dir, Dir *to_dir, string filename) {
  mutex_lock(&from_dir->lock);
  mutex_lock(&to_dir->lock);

  Map_put(to_dir->entries, filename,
        Map_get(from_dir->entries, filename));
  Map_erase(from_dir->entries, filename);

  mutex_unlock(&to_dir->lock);
  mutex_unlock(&from_dir->lock);
}
```

Thread 1: `MoveFile(A, B, "foo")`

Thread 2: `MoveFile(B, A, "bar")`

moving two files: lucky timeline (1)

Thread 1	Thread 2
`MoveFile(A, B, "foo")`	`MoveFile(B, A, "bar")`
`lock(&A->lock);`	
`lock(&B->lock);`	
(do move)	
`unlock(&B->lock);`	
`unlock(&A->lock);`	
	`lock(&B->lock);`
	`lock(&A->lock);`
	(do move)
	`unlock(&B->lock);`
	`unlock(&A->lock);`

moving two files: lucky timeline (2)

Thread 1	Thread 2
`MoveFile(A, B, "foo")`	`MoveFile(B, A, "bar")`
`lock(&A->lock);`	
`lock(&B->lock);`	
	`lock(&B->lock…`
(do move)	(waiting for B lock)
`unlock(&B->lock);`	
	`lock(&B->lock);`
	`lock(&A->lock…`
`unlock(&A->lock);`	
	`lock(&A->lock);`
	(do move)
	`unlock(&A->lock);`

moving two files: unlucky timeline

Thread 1	Thread 2
`MoveFile(A, B, "foo")`	`MoveFile(B, A, "bar")`
`lock(&A->lock);` ← interrupt	
	`lock(&B->lock);`

moving two files: unlucky timeline

Thread 1 `MoveFile(A, B, "foo")`	**Thread 2** `MoveFile(B, A, "bar")`
`lock(&A->lock);`	
	`lock(&B->lock);`
`lock(&B->lock...` stalled	
(waiting for lock on B)	`lock(&A->lock...` stalled
(waiting for lock on B)	(waiting for lock on A)

moving two files: unlucky timeline

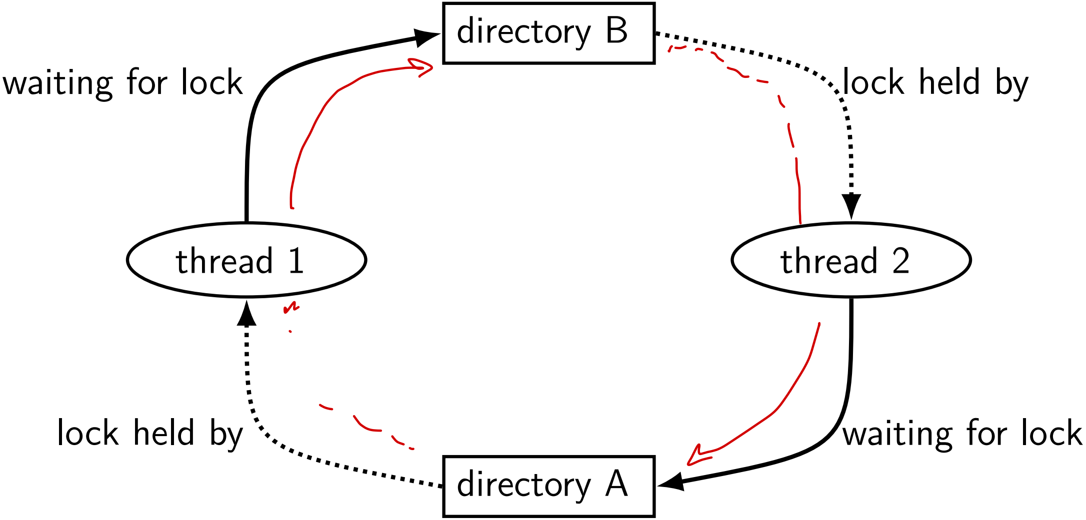
Thread 1	Thread 2
`MoveFile(A, B, "foo")`	`MoveFile(B, A, "bar")`
`lock(&A->lock);`	
	`lock(&B->lock);`
`lock(&B->lock…` stalled	
(waiting for lock on B)	`lock(&A->lock…` stalled
(waiting for lock on B)	(waiting for lock on A)
~~(do move)~~ unreachable	~~(do move)~~ unreachable
~~`unlock(&B->lock);`~~ unreachable	~~`unlock(&A->lock);`~~ unreachable
~~`unlock(&A->lock);`~~ unreachable	~~`unlock(&B->lock);`~~ unreachable

moving two files: unlucky timeline

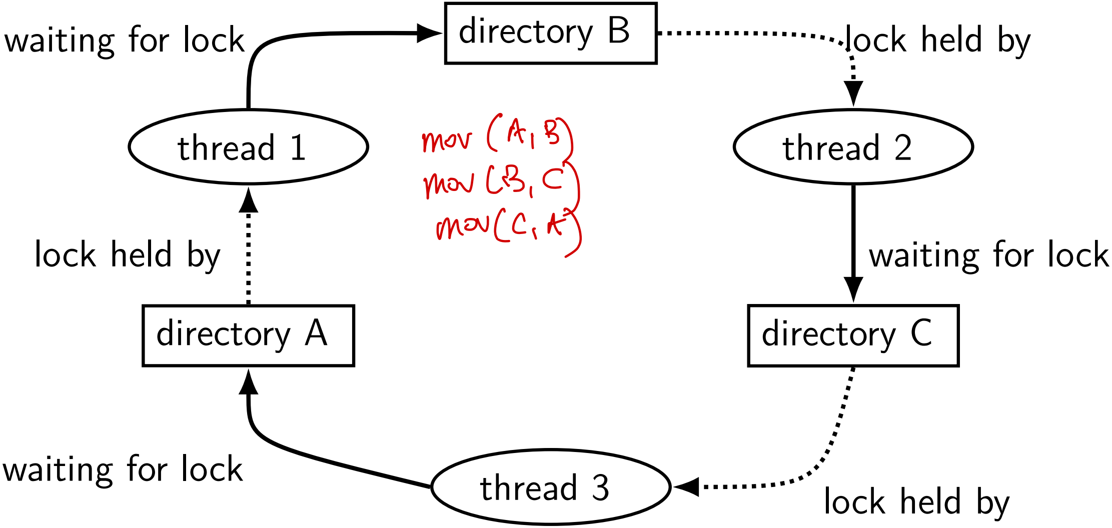
Thread 1 `MoveFile(A, B, "foo")`	Thread 2 `MoveFile(B, A, "bar")`
`lock(&A->lock);`	
	`lock(&B->lock);`
`lock(&B->lock`… stalled	
(waiting for lock on B)	`lock(&A->lock`… stalled
(waiting for lock on B)	(waiting for lock on A)
~~(do move)~~ unreachable	~~(do move)~~ unreachable
~~`unlock(&B->lock);`~~ unreachable	~~`unlock(&A->lock);`~~ unreachable
~~`unlock(&A->lock);`~~ unreachable	~~`unlock(&B->lock);`~~ unreachable

Thread 1 holds A lock, waiting for Thread 2 to release B lock

moving two files: dependencies



moving three files: dependencies



moving three files: unlucky timeline

Thread 1	Thread 2	Thread 3
`MoveFile(A, B, "foo")`	`MoveFile(B, C, "bar")`	`MoveFile(C, A, "quux")`
`lock(&A->lock);`		
	`lock(&B->lock);`	
		`lock(&C->lock);`
`lock(&B->lock…` stalled		
	`lock(&C->lock…` stalled	
		`lock(&A->lock…` stalled

deadlock with free space

Thread 1

```
AllocateOrWaitFor(1 MB)
AllocateOrWaitFor(1 MB)
(do calculation)
Free(1 MB)
Free(1 MB)
```

1

3rd

not avail

Thread 2

```
AllocateOrWaitFor(1 MB)
AllocateOrWaitFor(1 MB)
(do calculation)
Free(1 MB)
Free(1 MB)
```

2

4th

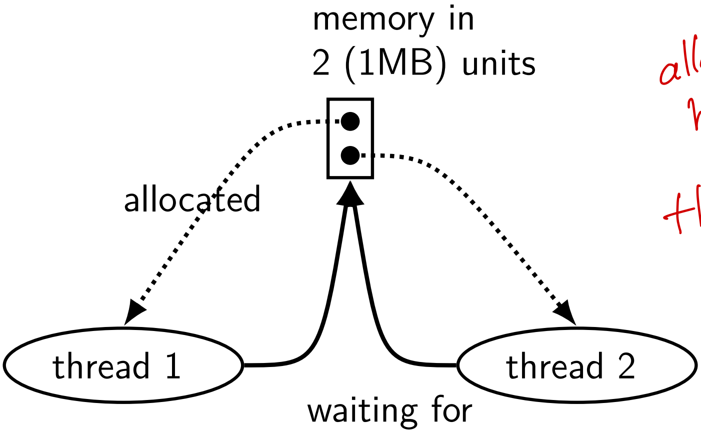
not avail

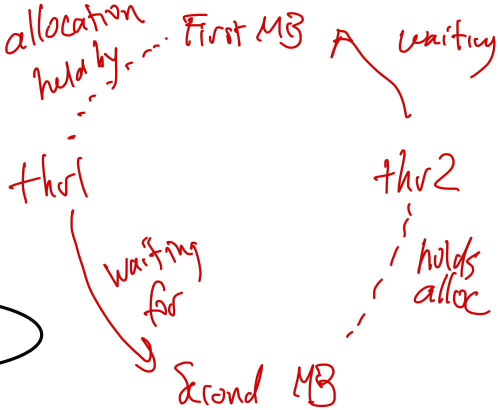
2 MB of space — deadlock possible with unlucky order

deadlock with free space (unlucky case)

Thread 1	Thread 2
`AllocateOrWaitFor(1 MB)`	
	`AllocateOrWaitFor(1 MB)`
`AllocateOrWaitFor(1 MB…` stalled	
	`AllocateOrWaitFor(1 MB…` stalled

free space: dependency graph





deadlock with free space (lucky case)

Thread 1

```
AllocateOrWaitFor(1 MB)
AllocateOrWaitFor(1 MB)
(do calculation)
Free(1 MB);
Free(1 MB);
```

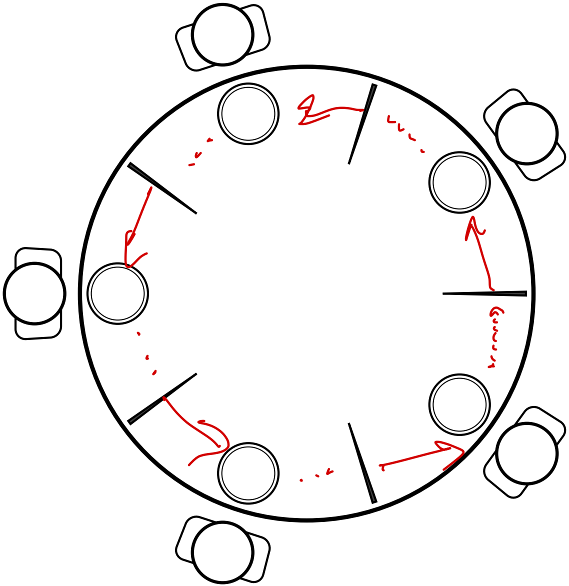
Thread 2

```
AllocateOrWaitFor(1 MB)
AllocateOrWaitFor(1 MB)
(do calculation)
Free(1 MB);
Free(1 MB);
```

lab next week

applying solutions to deadlock to classic *dining philosphers* problem

dining philosophers



five philosophers either think or eat

to eat:

chopstix[tid]

grab chopstick on left, then

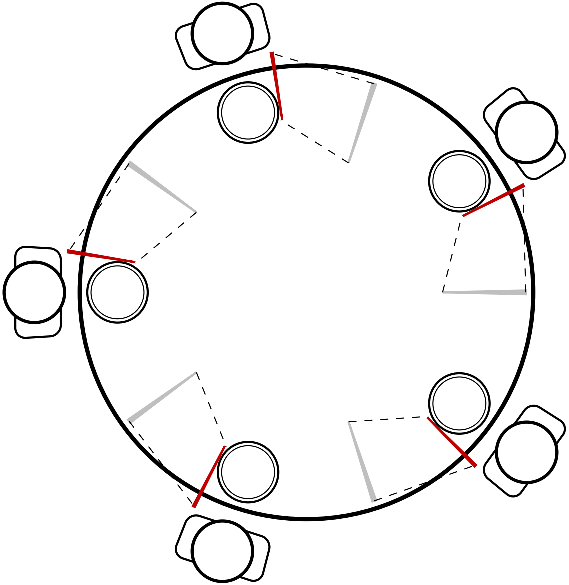
grba chopstick on right, then

then eat, then

chopstix[tid+1]

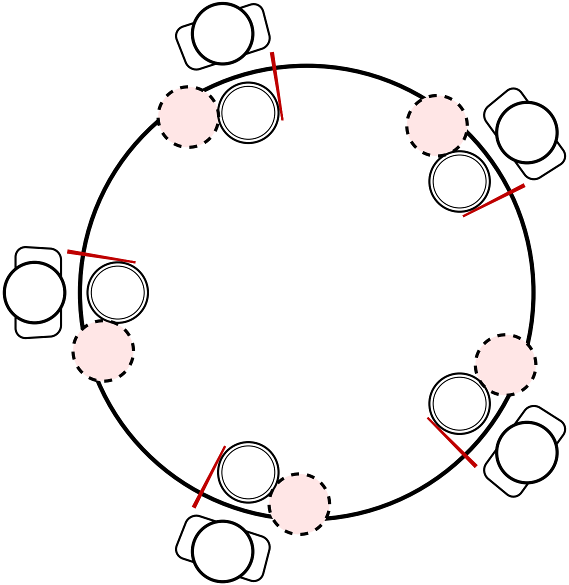
return chopsticks

dining philosophers



everyone eats at the same time?
grab left chopstick, then...

dining philosophers



everyone eats at the same time?
grab left chopstick, then
try to grab right chopstick, …
we're at an impasse

deadlock

deadlock — circular waiting for resources

resource = something needed by a thread to do work

- locks
- CPU time
- disk space
- memory
- ...

often non-deterministic in practice

most common example: when acquiring multiple locks

deadlock

deadlock — circular waiting for resources

resource = something needed by a thread to do work

- locks
- CPU time
- disk space
- memory
- ...

often non-deterministic in practice

most common example: when acquiring multiple locks

deadlock requirements

mutual exclusion

one thread at a time can use a resource

hold and wait

thread holding a resources waits to acquire *another* resource

no preemption of resources

resources are only released voluntarily

thread trying to acquire resources can't 'steal'

circular wait

there exists a set $\{T_1, \ldots, T_n\}$ of waiting threads such that

T_1 is waiting for a resource held by T_2

T_2 is waiting for a resource held by T_3

...

T_n is waiting for a resource held by T_1

how is deadlock possible?

Given list: A, B, C, D, E

```
RemoveNode(LinkedListNode *node) {
    pthread_mutex_lock(&node->lock);
    pthread_mutex_lock(&node->prev->lock);
    pthread_mutex_lock(&node->next->lock);
    node->next->prev = node->prev; node->prev->next = node->next;
    pthread_mutex_unlock(&node->next->lock); pthread_mutex_unlock(&node->p
    pthread_mutex_unlock(&node->lock);
}
```

Which of these (all run in parallel) can deadlock?

A. RemoveNode(B) and RemoveNode(C)
B. RemoveNode(B) and RemoveNode(D)
C. RemoveNode(B) and RemoveNode(C) and RemoveNode(D)
D. A and C
E. B and C
F. all of the above
G. none of the above

how is deadlock — solution

Remove B	Remove C
lock B	lock C
lock A (prev)	wait to lock B (prev)
wait to lock C (next)	

With B and D — only overlap in in node C — no circular wait possible
(thread can't be waiting while holding something other thread wants)

Rem B ← deadlock → Rem C ← deadlock → Rem D

Rem B
lock B
lock A
lock C

Rem D
lock D
lock C
lock E

deadlock prevention techniques

infinite resources or at least enough that never run out	no *mutual exclusion*
no shared resources	no *mutual exclusion*
no waiting "busy signal" — abort and (maybe) retry revoke/preempt resources	no *hold and wait*/ *preemption*
acquire resources in **consistent order**	no *circular wait*

deadlock prevention techniques

infinite resources

or at least enough that never run out

no *mutual exclusion*

no shared resources

no *mutual exclusion*

no waiting

"busy signal" — abort and (maybe) retry

revoke/preempt resources

no *hold and wait*/*preemption*

acquire resources in **consistent order**

no *circular wait*

deadlock prevention techniques

infinite resources — no *mutual exclusion*

or at least enough that never run out

no shared resources — no *mutual exclusion*

no waiting — no *hold and wait*/*preemption*

"busy signal" — abort and (maybe) retry

revoke/preempt resources

acquire resources in **consistent order** — no *circular wait*

deadlock prevention techniques

infinite resources — no *mutual exclusion*

or at least enough that never run out

memory allocation: malloc() fails rather than waiting (no deadlock)
locks: `pthread_mutex_trylock` fails rather than waiting
problem: retry how many times? no bound on number of tries needed
...

exclusion

no waiting — no *hold and wait*/ *preemption*

"busy signal" — abort and (maybe) retry

revoke/preempt resources

acquire resources in **consistent order** — no *circular wait*

deadlock prevention techniques

infinite resources or at least enough that never run out	no *mutual exclusion*
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no waiting "busy signal" — abort and (maybe) retry revoke/preempt resources	no *hold and wait*/ *preemption*
acquire resources in **consistent order**	no *circular wait*

deadlock prevention techniques

infinite resources — no *mutual exclusion*

or at least enough that never run out

no shared resources — no *mutual exclusion*

requires some way to undo partial changes to avoid errors
common approach for databases
...

no waiti — no *hold and wait*/ *preemption*

"busy signal" — abort and (maybe) retry

revoke/preempt resources

acquire resources in **consistent order** — no *circular wait*

deadlock prevention techniques

infinite resources or at least enough that never run out	no *mutual exclusion*
no shared resources	no *mutual exclusion*
no waiting "busy signal" — abort and (maybe) retry revoke/preempt resources	no *hold and wait*/ *preemption*
acquire resources in **consistent order**	no *circular wait*

acquiring locks in consistent order (1)

```
MoveFile(Dir* from_dir, Dir* to_dir, string filename) {
  if (from_dir->path < to_dir->path) {
    lock(&from_dir->lock);
    lock(&to_dir->lock);
  } else {
    lock(&to_dir->lock);
    lock(&from_dir->lock);
  }
  ...
}
```

Thr1 : mov(A, B) → lock A
lock B

Thr2: mov(B, A) → lock A
lock B

Thr1

lock A
lock B
mov A→B

Thr 2

stall on lock A
acq A
lock B
mov B→A

acquiring locks in consistent order (1)

```
MoveFile(Dir* from_dir, Dir* to_dir, string filename) {
  if (from_dir->path < to_dir->path) {
    lock(&from_dir->lock);
    lock(&to_dir->lock);
  } else {
    lock(&to_dir->lock);
    lock(&from_dir->lock);
  }
  ...
}
```

any ordering will do
e.g. compare pointers

or lexicographic sort
numerical sort

acquiring locks in consistent order (2)

often by convention, e.g. Linux kernel comments:

```
/*
 * ...
 * Lock order:
 *      contex.ldt_usr_sem
 *        mmap_sem
 *          context.lock
 */
```

```
/*
 * ...
 * Lock order:
 *   1. slab_mutex (Global Mutex)
 *   2. node->list_lock
 *   3. slab_lock(page) (Only on some arches and for debugging)
 * ...
 */
```

deadlock prevention techniques

infinite resources avoid

or at least enough that never run out

no *mutual exclusion*

no shared resources avoid

no *mutual exclusion*

no waiting avoid or break

"busy signal" — abort and (maybe) retry

revoke/preempt resources

no *hold and wait*/ *preemption*

acquire resources in **consistent order** avoid

no *circular wait*

backup slides

barriers

compute minimum of 100M element array with 2 processors

algorithm:

compute minimum of 50M of the elements on each CPU

- one thread for each CPU

wait for all computations to finish

take minimum of all the minimums

barriers

compute minimum of 100M element array with 2 processors

algorithm:

compute minimum of 50M of the elements on each CPU

- one thread for each CPU

wait for all computations to finish

take minimum of all the minimums

barriers API

barrier.Initialize(NumberOfThreads)

barrier.Wait() — return after all threads have waited

idea: multiple threads perform computations in parallel

threads wait for all other threads to call Wait()

barrier: waiting for finish

```
barrier.Initialize(2);
```

Thread 0

```
partial_mins[0] =
    /* min of first
       50M elems */;

barrier.Wait();


total_min = min(
    partial_mins[0],
    partial_mins[1]
);
```

Thread 1

```
partial_mins[1] =
    /* min of last
       50M elems */
barrier.Wait();
```

barriers: reuse

Thread 0

```
results[0][0] = getInitial(0);
barrier.Wait();

results[1][0] =
    computeFrom(
        results[0][0],
        results[0][1]
    );
barrier.Wait();

results[2][0] =
    computeFrom(
        results[1][0],
        results[1][1]
    );
```

Thread 1

```
results[0][1] = getInitial(1);
barrier.Wait();

results[1][1] =
    computeFrom(
        results[0][0],
        results[0][1]
    );
barrier.Wait();

results[2][1] =
    computeFrom(
        results[1][0],
        results[1][1]
    );
```

barriers: reuse

Thread 0

```
results[0][0] = getInitial(0);
barrier.Wait();

results[1][0] =
    computeFrom(
        results[0][0],
        results[0][1]
    );
barrier.Wait();

results[2][0] =
    computeFrom(
        results[1][0],
        results[1][1]
    );
```

Thread 1

```
results[0][1] = getInitial(1);
barrier.Wait();

results[1][1] =
    computeFrom(
        results[0][0],
        results[0][1]
    );
barrier.Wait();

results[2][1] =
    computeFrom(
        results[1][0],
        results[1][1]
    );
```

barriers: reuse

Thread 0	Thread 1

Thread 0

```
results[0][0] = getInitial(0);
barrier.Wait();

results[1][0] =
    computeFrom(
        results[0][0],
        results[0][1]
    );
barrier.Wait();

results[2][0] =
    computeFrom(
        results[1][0],
        results[1][1]
    );
```

Thread 1

```
results[0][1] = getInitial(1);
barrier.Wait();

results[1][1] =
    computeFrom(
        results[0][0],
        results[0][1]
    );
barrier.Wait();

results[2][1] =
    computeFrom(
        results[1][0],
        results[1][1]
    );
```

pthread barriers

```
pthread_barrier_t barrier;
pthread_barrier_init(
    &barrier,
    NULL /* attributes */,
    numberOfThreads
);
...
...
pthread_barrier_wait(&barrier);
```