哈爾濱工業大學
HARBIN INSTITUTE OF TECHNOLOGY

操作系统

Operating Systems

刘川意 教授

liuchuanyi@hit.edu.cn

哈尔滨工业大学（深圳）

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Module 5: Concurrency & Synchronization
并发与同步

1. **Concurrency Introduction**
2. **Locks**
3. **基于Lock的并发数据结构**
4. Condition Variables 条件变量
5. Semaphore 信号量
6. 常见并发问题
7. **基于事件的并发**

Concurrency为什么放到OS中讲？

- **History！**
  - OS Kernel是第一个并发程序，如:`write()`的设计，中断对shared structures的影响（page tables, process lists, file system structures, and virtually every kernel data structure has to be carefully accessed）
  - 很多并发处理技术是在OS中发明和实现的
  - multi-threade进程中，应用程序也需要考虑并发

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并发相关的重要术语

- **Critical Section,** a piece of code that accesses a *shared* resource, usually a variable or data structure
- **Race Condition** arises if multiple threads of execution enter the critical section at roughly the same time; both attempt to update the shared data structure, leading to a surprising (and perhaps undesirable) outcome.
- **Indeterminate,** program consists of one or more race conditions; the output of the program varies from run to run, depending on which threads ran when. The outcome is thus not **deterministic**, something we usually expect from computer systems.
- **Mutual Exclusion** primitives, guarantee that only a single thread ever enters a critical section, thus avoiding races, and resulting in deterministic program outputs

Review: Thread

- 轻量化执行环境，new abstraction for a single running process
- Multi-threaded 程序的特点：
  - A multi-threaded program has more than one point of execution.
  - Multiple PCs (Program Counter)
  - They share the same address space.

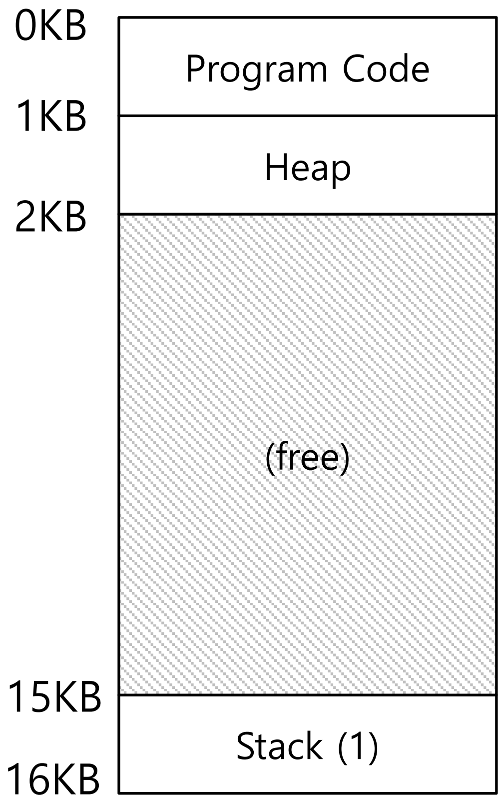
Context switch between threads

- Each thread has its own program counter and set of registers.
  - One or more **thread control blocks(TCBs)** are needed to store the state of each thread.

- When switching from running one (T1) to running the other (T2),
  - The register state of T1 be saved.
  - The register state of T2 restored.
  - The address space remains the same.

The stack of the relevant thread

- There will be one stack per thread.

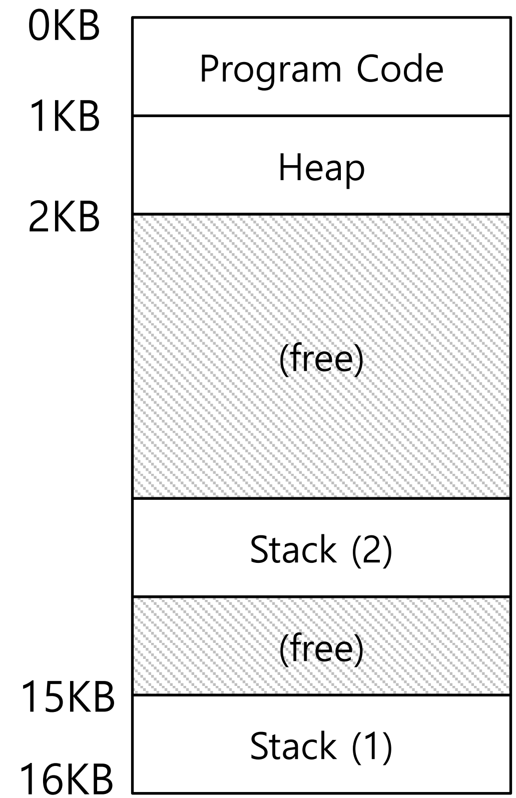


The code segment: where instructions live

The heap segment: contains malloc'd data dynamic data structures (it grows downward)

(it grows upward)
The stack segment: contains local variables arguments to routines, return values, etc.

A Single-Threaded Address Space



Two threaded Address Space

badcnt.c: Improper Synchronization

```c
/* Global shared variable */
volatile long cnt = 0; /* Counter */

int main(int argc, char **argv)
{
    long niters;
    pthread_t tid1, tid2;

    niters = atoi(argv[1]);
    Pthread_create(&tid1, NULL,
        thread, &niters);
    Pthread_create(&tid2, NULL,
        thread, &niters);
    Pthread_join(tid1, NULL);
    Pthread_join(tid2, NULL);

    /* Check result */
    if (cnt != (2 * niters))
        printf("BOOM! cnt=%ld\n", cnt);
    else
        printf("OK cnt=%ld\n", cnt);
    exit(0);
}
```

badcnt.c

```c
/* Thread routine */
void *thread(void *vargp)
{
    long i, niters =
                 *((long *)vargp);

    for (i = 0; i < niters; i++)
        cnt++;

    return NULL;
}
```

```
[zs_cao@localhost conc]$ ./badcnt 10000
OK cnt=20000
[zs_cao@localhost conc]$ ./badcnt 10000
BOOM! cnt=17302
[zs_cao@localhost conc]$ ./badcnt 10000
OK cnt=20000
```

线程并发执行的问题

Assembly Code for Counter Loop

- 编译:
  - gcc –s badcnt.c –o badcnt.s
  - vim badcnt.s

```
for (i = 0; i < niters; i++)
    cnt++;
```

```
        movq    %rdi, -24(%rbp)
        movq    -24(%rbp), %rax
        movq    (%rax), %rax
        movq    %rax, -8(%rbp)
        movq    $0, -16(%rbp)
        jmp     .L6
.L7:
        movq    cnt(%rip), %rax
        addq    $1, %rax
        movq    %rax, cnt(%rip)
        addq    $1, -16(%rbp)
.L6:
        movq    -16(%rbp), %rax
        cmpq    -8(%rbp), %rax
        jl      .L7
        movl    $0, %eax
        popq    %rbp
```

H_i : Head

L_i : Load `cnt`

U_i : Update `cnt`

S_i : Store `cnt`

T_i : Tail

Assembly Code for Counter Loop

- 汇编:
  - gcc –c badcnt.s –o badcnt.o
  - objdump -dx badcnt.o

```
for (i = 0; i < niters; i++)
    cnt++;
```

```
00000000000000ed <thread>:
  ed:   55                      push   %rbp
  ee:   48 89 e5                mov    %rsp,%rbp
  f1:   48 89 7d e8             mov    %rdi,-0x18(%rbp)
  f5:   48 8b 45 e8             mov    -0x18(%rbp),%rax
  f9:   48 8b 00                mov    (%rax),%rax
  fc:   48 89 45 f8             mov    %rax,-0x8(%rbp)
 100:   48 c7 45 f0 00 00 00    movq   $0x0,-0x10(%rbp)
 107:   00
 108:   eb 17                   jmp    121 <thread+0x34>
 10a:   48 8b 05 00 00 00 00    mov    0x0(%rip),%rax        # 111
<thread+0x24>
                        10d: R_X86_64_PC32      cnt-0x4
 111:   48 83 c0 01             add    $0x1,%rax
 115:   48 89 05 00 00 00 00    mov    %rax,0x0(%rip)        # 11c
<thread+0x2f>
                        118: R_X86_64_PC32      cnt-0x4
 11c:   48 83 45 f0 01          addq   $0x1,-0x10(%rbp)
 121:   48 8b 45 f0             mov    -0x10(%rbp),%rax
 125:   48 3b 45 f8             cmp    -0x8(%rbp),%rax
 129:   7c df                   jl     10a <thread+0x1d>
 12b:   b8 00 00 00 00          mov    $0x0,%eax
 130:   5d                      pop    %rbp
 131:   c3                      retq
```

H_i

L_i

U_i

S_i

T_i

Assembly Code for Counter Loop

- 链接:
  - gcc –o badcnt.c –o badcnt -lpthread
  - objdump -d badcnt

```
for (i = 0; i < niters; i++)
    cnt++;
```

怎么计算？

```
0000000000000957 <thread>:
 957:   55                      push   %rbp
 958:   48 89 e5                mov    %rsp,%rbp
 95b:   48 89 7d e8             mov    %rdi,-0x18(%rbp)
 95f:   48 8b 45 e8             mov    -0x18(%rbp),%rax
 963:   48 8b 00                mov    (%rax),%rax
 966:   48 89 45 f8             mov    %rax,-0x8(%rbp)
 96a:   48 c7 45 f0 00 00 00    movq   $0x0,-0x10(%rbp)
 971:   00
 972:   eb 17                   jmp    98b <thread+0x34>
 974:   48 8b 05 b5 06 20 00    mov    0x2006b5(%rip),%rax
  # 201030 <cnt>
 97b:   48 83 c0 01             add    $0x1,%rax
 97f:   48 89 05 aa 06 20 00    mov    %rax,0x2006aa(%rip)
  # 201030 <cnt>
 986:   48 83 45 f0 01          addq   $0x1,-0x10(%rbp)
 98b:   48 8b 45 f0             mov    -0x10(%rbp),%rax
 98f:   48 3b 45 f8             cmp    -0x8(%rbp),%rax
 993:   7c df                   jl     974 <thread+0x1d>
 995:   b8 00 00 00 00          mov    $0x0,%eax
 99a:   5d                      pop    %rbp
 99b:   c3                      retq
```

H_i

L_i

U_i

S_i

T_i

Race condition

- 把上述示例简化一下：
  - counter = counter + 1 (default is 50)
  - We expect the result is 52. However,

OS	Thread1	Thread2	(after instruction)		
			PC	%eax	counter
	`before critical section`		100	0	50
	`mov 0x8049a1c, %eax`		105	50	50
	`add $0x1, %eax`		108	51	50
`interrupt`					
`save T1's state`					
`restore T2's state`			100	0	50
		`mov 0x8049a1c, %eax`	105	50	50
		`add $0x1, %eax`	108	51	50
		`mov %eax, 0x8049a1c`	113	51	51
`interrupt`					
`save T2's state`					
`restore T1's state`			108	51	50
	`mov %eax, 0x8049a1c`		113	51	$\boxed{\mathbf{51}}$

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Critical section

- A piece of code that accesses a shared variable and must not be concurrently executed by more than one thread.
  - Multiple threads executing critical section can result in a race condition.
  - Need to support **atomicity** for critical sections (**mutual exclusion**)

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Locks

- Ensure that any such critical section executes as if it were a single atomic instruction (**execute a series of instructions atomically**).

```
lock_t mutex;
. . .
lock(&mutex);
balance = balance + 1;
unlock(&mutex);
```

Critical section

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Concurrent Execution(并发执行)

- *Key idea:* In general, any sequentially consistent interleaving is possible, but some give an unexpected result!
  - I_i denotes that thread i executes instruction I
  - $\%rdx_i$ is the content of %rdx in thread i's context

i (thread)	$instr_i$	$\%rdx_1$	$\%rdx_2$	cnt
1	H_1	-	-	0
1	L_1	0	-	0
1	U_1	1	-	0
1	S_1	1	-	1
2	H_2	-	-	1
2	L_2	-	1	1
2	U_2	-	2	1
2	S_2	-	2	2
2	T_2	-	2	2
1	T_1	1	-	2

Thread 1 critical section

Thread 2 critical section

OK

Concurrent Execution (cont)

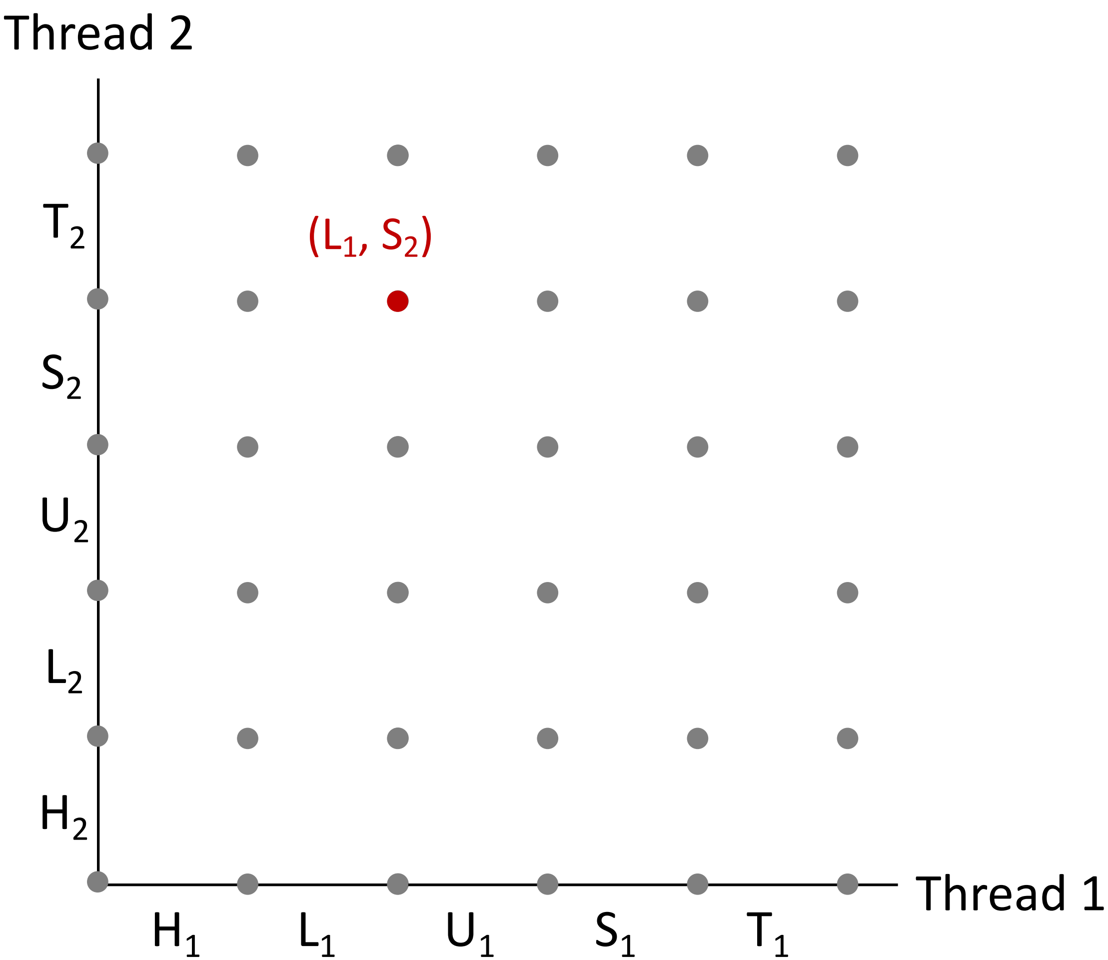
- Incorrect ordering: two threads increment the counter, but the result is 1 instead of 2

i (thread)	$instr_i$	$\%rdx_1$	$\%rdx_2$	cnt
1	H_1	-	-	0
1	L_1	0	-	0
1	U_1	1	-	0
2	H_2			0
2	L_2	-	0	0
1	S_1	1	-	1
1	T_1	1	-	1
2	U_2	-	1	1
2	S_2	-	1	1
2	T_2	-	1	1

S1应该在L2之前执行

Oops!

Progress Graphs（进度图）



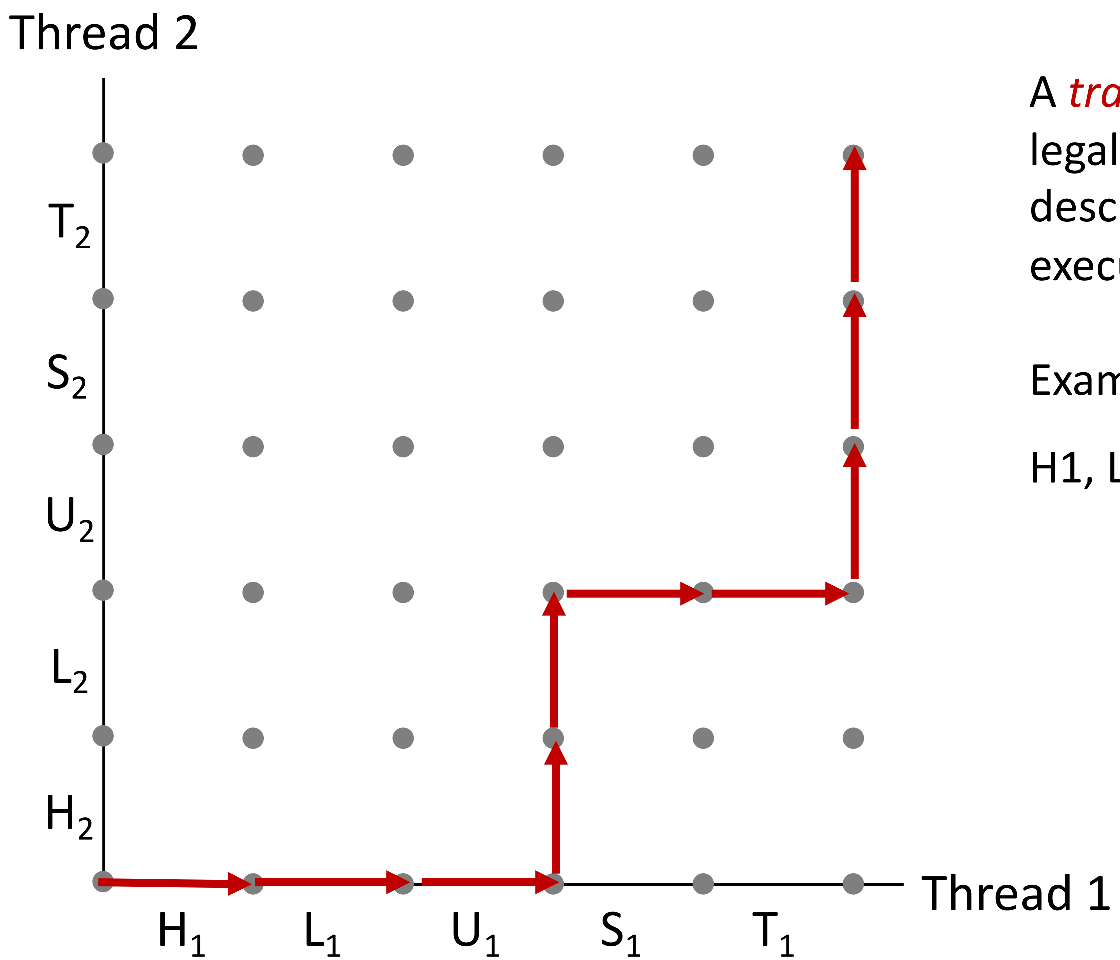
A *progress graph* depicts the discrete *execution state space* of concurrent threads.

Each axis corresponds to the sequential order of instructions in a thread.

Each point corresponds to a possible *execution state* $(Inst_1, Inst_2)$.

E.g., (L_1, S_2) denotes state where thread 1 has completed L_1 and thread 2 has completed S_2.

Trajectories in Progress Graphs

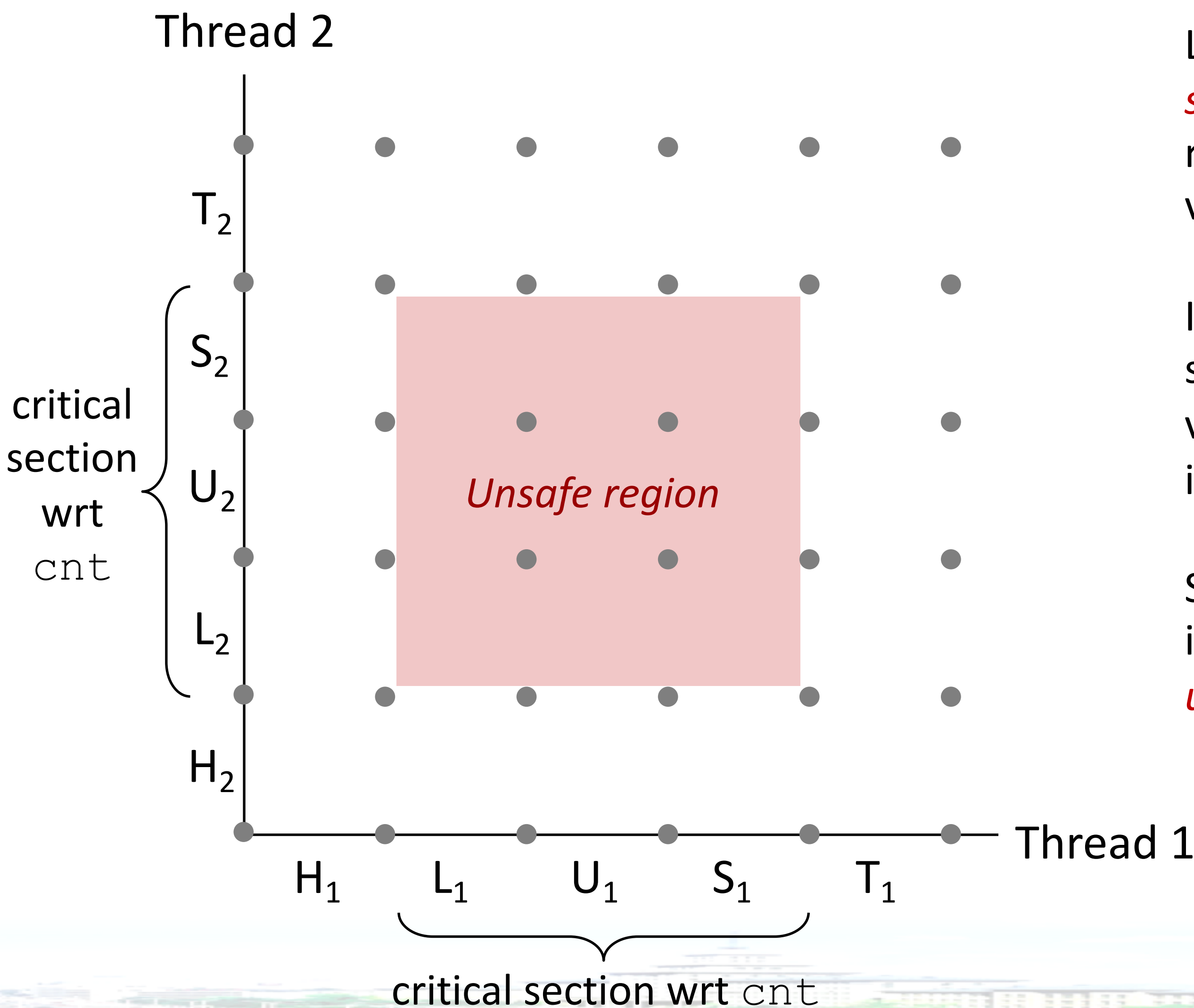


A *trajectory*（轨道）is a sequence of legal state transitions（转换）that describes one possible concurrent execution of the threads.

Example:

H1, L1, U1, H2, L2, S1, T1, U2, S2, T2

Critical Sections and Unsafe Regions

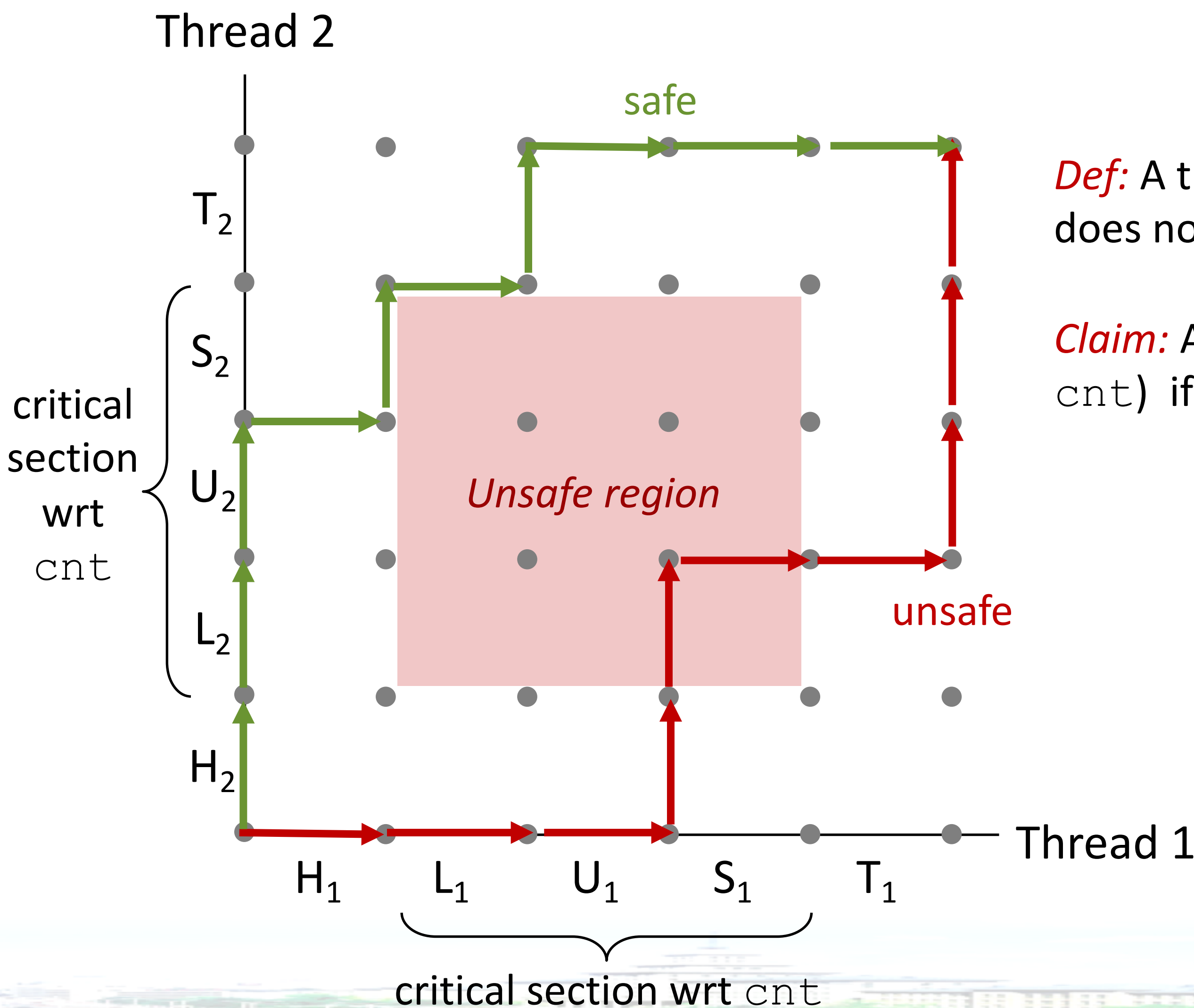


L, U, and S form a *critical section（临界区）*with respect to the shared variable `cnt`

Instructions in critical sections (wrt some shared variable) should not be interleaved

Sets of states where such interleaving occurs form *unsafe regions*

Critical Sections and Unsafe Regions



Def: A trajectory（轨道）is *safe* iff it does not enter any unsafe region

Claim: A trajectory is correct (wrt `cnt`) iff it is safe

Enforcing Mutual Exclusion

- *Question:* How can we guarantee a safe trajectory?

- Answer: We must ***synchronize*** *（同步）*the execution of the threads so that they can never have an unsafe trajectory.
  - i.e., need to guarantee ***mutually exclusive access（互斥地访问）*** for each critical section.

- Classic solution:
  - Semaphores（信号量）(Edsger Dijkstra)

- Other approaches (out of our scope)
  - Mutex and condition variables (Pthreads)
  - Monitors (Java)

信号处理

【例题1】子进程运行结束会向父进程发送______信号。

【例题2】异步信号安全的函数要么是可重入的，要么不能被信号处理程序中断，包括I/O函数（）

A.printf　　B.sprintf　　C.write　　D.malloc

答案：**SIGCHLD/17号　　C**

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Locks: The Basic Idea

- Ensure that any **critical section** executes as if it were a single atomic instruction. “全部或都不”
  - Eg. update of a shared variable

```
balance = balance + 1;
```

  - Add some code around the critical section

```
lock_t mutex; // some globally-allocated lock 'mutex'
…
lock(&mutex);
balance = balance + 1;
unlock(&mutex);
```


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Lock变量

- Lock variable holds the state of the lock.
  - **available** (or **unlocked** or **free**)
    - No thread holds the lock.
  - **acquired** (or **locked** or **held**)
    - Exactly one thread holds the lock and presumably is in a critical section.

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lock()原语的语义（semantics）

- `lock()`
  - **Try to** acquire the lock.
  - If <u>no other thread holds</u> the lock, the thread will **acquire** the lock.
  - **Enter** the *critical section*.
    - This thread is said to be <u>the owner of</u> the lock.
  - Other threads are *prevented from* entering the critical section while the first thread that holds the lock is in there.

Pthread Locks - mutex

- The name that the POSIX library uses for a lock.
  - Used to provide mutual exclusion between threads.

```
pthread_mutex_t lock = PTHREAD_MUTEX_INITIALIZER;

Pthread_mutex_lock(&lock); // wrapper for pthread_mutex_lock()
balance = balance + 1;
Pthread_mutex_unlock(&lock);
```

  - We may be using *different locks* to protect *different variables* → Increase concurrency (a more **fine-grained** approach).

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Lock如何实现？

- Efficient locks provided mutual exclusion at low cost.
- Building a lock need some help from the **hardware** and the **OS**.

如何评价lock原语？

- **Mutual exclusion 正确性**
  - Does the lock work, preventing multiple threads from entering *a critical section*?
- **Fairness 公平性**
  - Does each thread contending for the lock get a fair shot at acquiring it once it is free? (Starvation)
- **Performance 性能**
  - The time overheads added by using the lock

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Controlling Interrupts 基于中断控制的锁实现

- **Disable Interrupts** for critical sections
  - One of the earliest solutions used to provide mutual exclusion
  - Invented for single-processor systems.

```
void lock() {
    DisableInterrupts();
}
void unlock() {
    EnableInterrupts();
}
```

  - Problem:
    - Require too much *trust* in applications
      - Greedy (or malicious) program could monopolize the processor.
    - Do not work on multiprocessors 多处理器体系结构这种方式不work
    - Code that masks or unmasks interrupts be executed *slowly* by modern CPUs

Why hardware support needed?

- **First attempt**: Using a *flag* denoting whether the lock is held or not.
  - The code below has problems.

```
typedef struct __lock_t { int flag; } lock_t;

void init(lock_t *mutex) {
    // 0 → lock is available, 1 → held
    mutex->flag = 0;
}

void lock(lock_t *mutex) {
    while (mutex->flag == 1)  // TEST the flag
            ;  // spin-wait (do nothing)
    mutex->flag = 1;  // now SET it !
}

void unlock(lock_t *mutex) {
    mutex->flag = 0;
}
```


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Why hardware support needed? (Cont.)

- **Problem 1**: No Mutual Exclusion (assume `flag=0` to begin)

Thread1	Thread2
call `lock()`	
`while (flag == 1)`	
interrupt: switch to Thread 2	
	call `lock()`
	`while (flag == 1)`
	`flag = 1;`
	interrupt: switch to Thread 1

- **Problem 2**: Spin-waiting wastes time waiting for another thread.

```
flag = 1; // set flag to 1 (too!)
```

- So, we need an atomic instruction supported by Hardware!
  - ***test-and-set* instruction**, also known as ***atomic exchange***

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基于Test-and-set硬件指令实现

- An instruction to support the creation of simple locks

```
int TestAndSet(int *ptr, int new) {
    int old = *ptr;          // fetch old value at ptr
    *ptr = new;     // store 'new' into ptr
    return old;     // return the old value
}
```

- **return**(testing) old value pointed to by the `ptr`.
- *Simultaneously* **update**(setting) said value to `new`.
- This sequence of operations is performed atomically.

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A Simple Spin Lock using test-and-set


```
typedef struct __lock_t {
        int flag;
} lock_t;

void init(lock_t *lock) {
        // 0 indicates that lock is available,
        // 1 that it is held
        lock->flag = 0;
}

void lock(lock_t *lock) {
        while (TestAndSet(&lock->flag, 1) == 1)
                ;        // spin-wait
}

void unlock(lock_t *lock) {
        lock->flag = 0;
}
```

- **Note**: To work correctly on *a single processor*, it requires a preemptive scheduler.
- 在单处理器体系结构中，需要OS kernel实现抢占式调度策略来支持

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Evaluating Spin Locks

- **Correctness**: yes
  - The spin lock only allows a single thread to entry the critical section.
- **Fairness**: no
  - Spin locks <u>don’t provide any fairness</u> guarantees.
  - Indeed, a thread spinning may spin *forever*.
- **Performance**:
  - In the single CPU, performance overheads can be quire *painful*.
  - If the number of threads roughly equals the number of CPUs, spin locks work *reasonably well*.

基于Compare-And-Swap硬件指令实现

- Test whether the value at the address(`ptr`) is equal to `expected`.
  - *If so*, update the memory location pointed to by `ptr` with the `new` value.
  - *In either case*, return the actual value at that memory location.

```
int CompareAndSwap(int *ptr, int expected, int new) {
     int actual = *ptr;
     if (actual == expected)
             *ptr = new;
     return actual;
}
```

Compare-and-Swap hardware atomic instruction (C-style)

```
void lock(lock_t *lock) {
     while (CompareAndSwap(&lock->flag, 0, 1) == 1)
             ; // spin
}
```

Spin lock with compare-and-swap

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Compare-And-Swap (Cont.)

- C-callable x86-version of compare-and-swap

```
char CompareAndSwap(int *ptr, int old, int new) {
    unsigned char ret;

    // Note that sete sets a 'byte' not the word
    __asm__ __volatile__ (
            " lock\n"
            " cmpxchgl %2,%1\n"
            " sete %0\n"
            : "=q" (ret), "=m" (*ptr)
            : "r" (new), "m" (*ptr), "a" (old)
            : "memory");
    return ret;
}
```


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Load-Linked and Store-Conditional

```
int LoadLinked(int *ptr) {
    return *ptr;
}

int StoreConditional(int *ptr, int value) {
  if (no one has updated *ptr since the LoadLinked to this address) {
    *ptr = value;
    return 1; // success!
  } else {
    return 0; // failed to update
  }
}
```

Load-linked And Store-conditional

- The store-conditional *only succeeds* if no intermittent store to the address has taken place.
  - **success**: return 1 and <u>update</u> the value at `ptr` to `value`.
  - **fail**: the value at `ptr` is <u>not updates</u> and 0 is returned.

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Load-Linked and Store-Conditional (Cont.)

```
void lock(lock_t *lock) {
    while (1) {
        while (LoadLinked(&lock->flag) == 1)
            ; // spin until it's zero
        if (StoreConditional(&lock->flag, 1) == 1)
            return; // if set-it-to-1 was a success: all done
                    otherwise: try it all over again
    }
}

void unlock(lock_t *lock) {
    lock->flag = 0;
}
```

Using LL/SC To Build A Lock

```
void lock(lock_t *lock) {
    while (LoadLinked(&lock->flag)||!StoreConditional(&lock->flag, 1))
        ; // spin
}
```

A more concise form of the `lock()` using LL/SC

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Fetch-And-Add

- Atomically increment a value while returning the old value at a particular address.

```c
int FetchAndAdd(int *ptr) {
    int old = *ptr;
    *ptr = old + 1;
    return old;
}
```

Fetch-And-Add Hardware atomic instruction (C-style)

Ticket Lock

- **Ticket lock** can be built with fetch-and add.
  - Ensure progress for all threads. → fairness

```c
typedef struct __lock_t {
    int ticket;
    int turn;
} lock_t;

void lock_init(lock_t *lock) {
    lock->ticket = 0;
    lock->turn = 0;
}

void lock(lock_t *lock) {
    int myturn = FetchAndAdd(&lock->ticket);
    while (lock->turn != myturn)
        ; // spin
}
void unlock(lock_t *lock) {
    FetchAndAdd(&lock->turn);
}
```


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So Much Spinning

- Hardware-based spin locks are simple and they work.

- In some cases, these solutions can be quite inefficient.
  - Any time a thread gets caught *spinning*, it **wastes an entire time slice** doing nothing but checking a value.

How To Avoid *Spinning*?
We'll need OS Support too!

如何解决“自旋空转”，办法1：Just Yield

- When you are going to spin, give up the CPU to another thread.
  - OS system call moves the caller from the *running state* to the *ready state*.
  - The cost of a **context switch** can be substantial and the **starvation** problem still exists.

```
void init() {
    flag = 0;
}

void lock() {
    while (TestAndSet(&flag, 1) == 1)
        yield(); // give up the CPU
}

void unlock() {
    flag = 0;
}
```

Lock with Test-and-set and Yield

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办法2：Using Queues: Sleeping, not Spinning

- **Queue** to keep track of which threads are waiting to enter the lock.
- `park()`
  - Put a calling thread to sleep
- `unpark(threadID)`
  - Wake a particular thread as designated by `threadID`.

Using Queues: Sleeping Instead of Spinning

```c
typedef struct __lock_t { int flag; int guard; queue_t *q; } lock_t;

void lock_init(lock_t *m) {
    m->flag = 0;
    m->guard = 0;
    queue_init(m->q);
}

void lock(lock_t *m) {
    while (TestAndSet(&m->guard, 1) == 1)
        ; // acquire guard lock by spinning
    if (m->flag == 0) {
        m->flag = 1; // lock is acquired
        m->guard = 0;
    } else {
        queue_add(m->q, gettid());
        m->guard = 0;
        park();
    }
}
…
```

Lock With Queues, Test-and-set, Yield, And Wakeup

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Using Queues: Sleeping Instead of Spinning

```
void unlock(lock_t *m) {
    while (TestAndSet(&m->guard, 1) == 1)
        ; // acquire guard lock by spinning
    if (queue_empty(m->q))
        m->flag = 0; // let go of lock; no one wants it
    else
        unpark(queue_remove(m->q)); // hold lock (for next thread!)
    m->guard = 0;
}
```

Lock With Queues, Test-and-set, Yield, And Wakeup (Cont.)

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Futex (Cont.)

```
                if (v >= 0)
                        continue;
                futex_wait(mutex, v);
        }
}

void mutex_unlock(int *mutex) {
        /* Adding 0x80000000 to the counter results in 0 if and only if
           there are not other interested threads */
        if (atomic_add_zero(mutex, 0x80000000))
                return;
        /* There are other threads waiting for this mutex,
           wake one of them up */
        futex_wake(mutex);
}
```

Linux-based Futex Locks (Cont.)

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Two-Phase Locks

- A two-phase lock realizes that spinning can be useful if the lock *is about to* be released.
  - **First phase**
    - The lock spins for a while, *hoping that* it can acquire the lock.
    - If the lock is not acquired during the first spin phase, a second phase is entered,
  - **Second phase**
    - The caller is put to sleep.
    - The caller is only woken up when the lock becomes free later.

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Module 5: Concurrency & Synchronization
并发与同步

1. **Concurrency Introduction**
2. **Locks**
3. **基于Lock的并发数据结构**
4. Condition Variables 条件变量
5. Semaphore 信号量
6. 常见并发问题
7. 基于事件的并发

Lock-based Concurrent Data structure

- Adding locks to a data structure makes the structure **thread safe**.
  - How locks are added determine both the correctness and performance of the data structure.

Example: Concurrent Counter without Lock

- Simple but not scalable

```
typedef struct __counter_t {
        int value;
} counter_t;

void init(counter_t *c) {
        c->value = 0;
}

void increment(counter_t *c) {
        c->value++;
}

void decrement(counter_t *c) {
        c->value--;
}

int get(counter_t *c) {
        return c->value;
}
```


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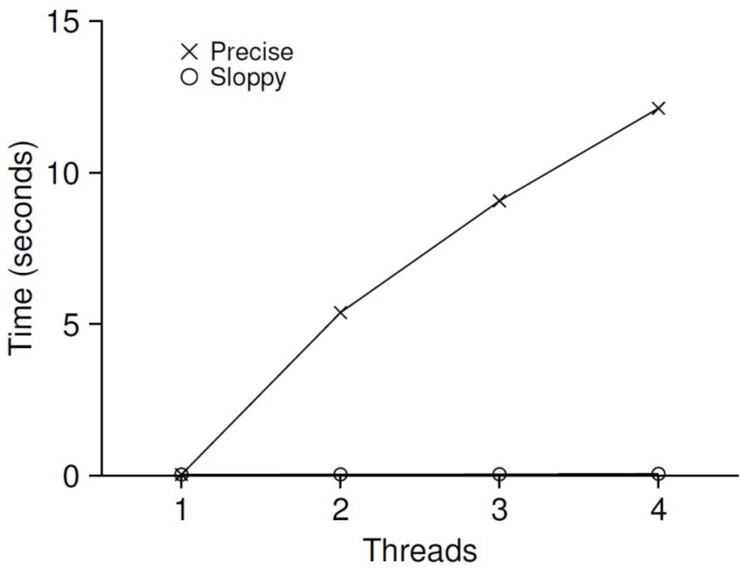
Add a single lock

- acquired when calling a routine manipulating the data structure.

```
typedef struct __counter_t {
        int value;
        pthread_lock_t lock;
} counter_t;

void init(counter_t *c) {
        c->value = 0;
        Pthread_mutex_init(&c->lock, NULL);
}

void increment(counter_t *c) {
        Pthread_mutex_lock(&c->lock);
        c->value++;
        Pthread_mutex_unlock(&c->lock);
}
void decrement(counter_t *c) {
        Pthread_mutex_lock(&c->lock);
        c->value--;
        Pthread_mutex_unlock(&c->lock);
}

int get(counter_t *c) {
        Pthread_mutex_lock(&c->lock);
        int rc = c->value;
        Pthread_mutex_unlock(&c->lock);
        return rc;
}
```

The performance cost of the simple approach

- Each thread updates a single shared counter.
  - Each thread updates the counter one million times.
  - iMac with four Intel 2.7GHz i5 CPUs.



Performance of Traditional vs. Sloppy Counters
(Threshold of Sloppy, S, is set to 1024)

Synchronized counter scales poorly.

Perfect Scaling

- Even though more work is done, it is **done in parallel**.
- The time taken to complete the task is *not increased*.

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Sloppy counter

- The sloppy counter works by representing …
  - A single **logical counter** via numerous local physical counters, <u>on per CPU core</u>
  - A single **global counter**
  - There are **lock**s:
    - One fore each local counter and one for the global counter

- Example: on a machine with four CPUs
  - Four local counters
  - One global counter

The basic idea of sloppy counting

- When a thread running on a core wishes to increment the counter.
  - It increment its local counter.
  - Each CPU has its own local counter:
    - Threads across CPUs can update local counters *without contention*.
    - Thus counter updates are scalable.
  - The local values are periodically transferred to the global counter.
    - Acquire the global lock
    - Increment it by the local counter's value
    - The local counter is then reset to zero.

The basic idea of sloppy counting (Cont.)

- How often the local-to-global transfer occurs is determined by a threshold, S (sloppiness).
  - The smaller S:
    - The more the counter behaves like the *non-scalable counter*.
  - The bigger S:
    - The more scalable the counter.
    - The further off the global value might be from the *actual count*.

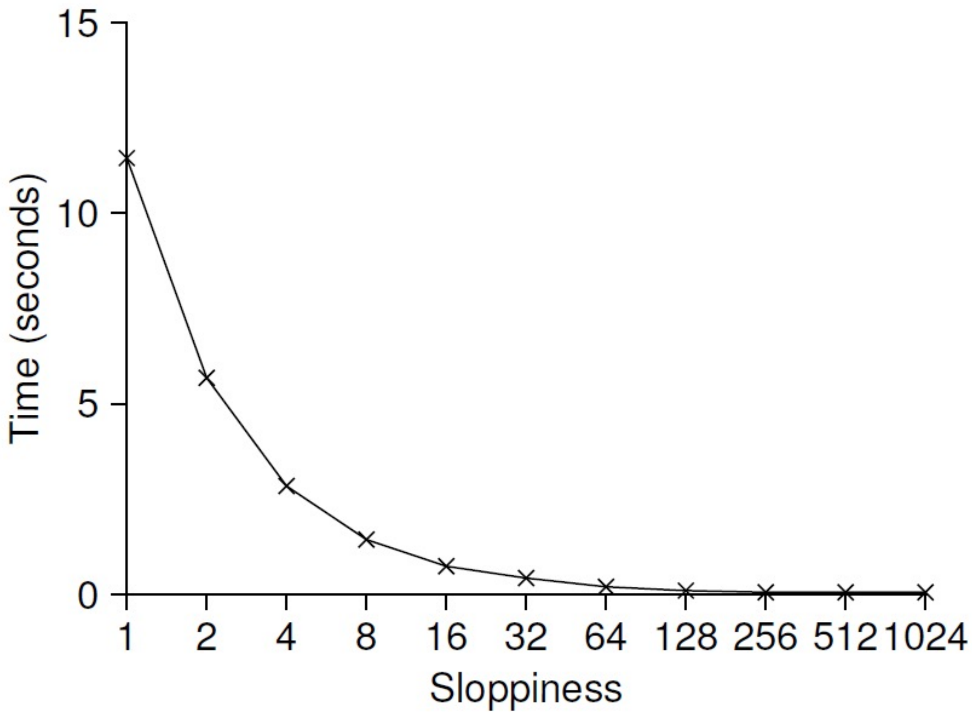
Sloppy counter example

- Tracing the Sloppy Counters
  - The threshold S is set to 5.
  - There are threads on each of 4 CPUs
  - Each thread updates their local counters $L_1 \dots L_4$.

Time	L_1	L_2	L_3	L_4	G
0	0	0	0	0	0
1	0	0	1	1	0
2	1	0	2	1	0
3	2	0	3	1	0
4	3	0	3	2	0
5	4	1	3	3	0
6	5 → 0	1	3	4	5 (from L_1)
7	0	2	4	5 → 0	10 (from L_4)

Importance of the threshold value *S*

- Each four threads increments a counter 1 million times on four CPUs.
  - Low S → Performance is **poor**, The global count is always quire **accurate**.
  - High S → Performance is **excellent**, The global count **lags**.



Scaling Sloppy Counters

Sloppy Counter Implementation

```
typedef struct __counter_t {
    int global;                 // global count
    pthread_mutex_t glock;      // global lock
    int local[NUMCPUS];         // local count (per cpu)
    pthread_mutex_t llock[NUMCPUS]; // ... and locks
    int threshold;      // update frequency
} counter_t;

// init: record threshold, init locks, init values
//       of all local counts and global count
void init(counter_t *c, int threshold) {
    c->thres hold = threshold;

    c->global = 0;
    pthread_mutex_init(&c->glock, NULL);

    int i;
    for (i = 0; i < NUMCPUS; i++) {
        c->local[i] = 0;
        pthread_mutex_init(&c->llock[i], NULL);
    }
}

```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Sloppy Counter Implementation (Cont.)

```
(Cont.)
    // update: usually, just grab local lock and update local amount
    //         once local count has risen by 'threshold', grab global
    //         lock and transfer local values to it
    void update(counter_t *c, int threadID, int amt) {
        pthread_mutex_lock(&c->llock[threadID]);
        c->local[threadID] += amt;          // assumes amt > 0
        if (c->local[threadID] >= c->threshold) { // transfer to global
            pthread_mutex_lock(&c->glock);
            c->global += c->local[threadID];
            pthread_mutex_unlock(&c->glock);
            c->local[threadID] = 0;
        }
        pthread_mutex_unlock(&c->llock[threadID]);
    }

    // get: just return global amount (which may not be perfect)
    int get(counter_t *c) {
        pthread_mutex_lock(&c->glock);
        int val = c->global;
        pthread_mutex_unlock(&c->glock);
        return val;         // only approximate!
    }
```

Concurrent Linked Lists

```
// basic node structure
typedef struct __node_t {
        int key;
        struct __node_t *next;
} node_t;

// basic list structure (one used per list)
typedef struct __list_t {
        node_t *head;
        pthread_mutex_t lock;
} list_t;

void List_Init(list_t *L) {
        L->head = NULL;
        pthread_mutex_init(&L->lock, NULL);
}

```

(Cont.)

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Concurrent Linked Lists

(Cont.)

```
    int List_Insert(list_t *L, int key) {
        pthread_mutex_lock(&L->lock);
        node_t *new = malloc(sizeof(node_t));
        if (new == NULL) {
            perror("malloc");
            pthread_mutex_unlock(&L->lock);
        return -1; // fail
        new->key = key;
        new->next = L->head;
        L->head = new;
        pthread_mutex_unlock(&L->lock);
        return 0; // success
}
    int List_Lookup(list_t *L, int key) {
        pthread_mutex_lock(&L->lock);
        node_t *curr = L->head;
        while (curr) {
            if (curr->key == key) {
                pthread_mutex_unlock(&L->lock);
                return 0; // success
            }
            curr = curr->next;
        }
        pthread_mutex_unlock(&L->lock);
        return -1; // failure
    }
```

Concurrent Linked Lists (Cont.)

- The code **acquires** a lock in the insert routine upon entry.
- The code **releases** the lock upon exit.
  - If `malloc()` happens to *fail*, the code must also <u>release the lock</u> before failing the insert.
  - This kind of exceptional control flow has been shown to be quite error prone.
  - **Solution**: The lock and release *only surround* the actual critical section in the insert code

Concurrent Linked List: Rewritten

```
void List_Init(list_t *L) {
        L->head = NULL;
        pthread_mutex_init(&L->lock, NULL);
}

void List_Insert(list_t *L, int key) {
        // synchronization not needed
        node_t *new = malloc(sizeof(node_t));
        if (new == NULL) {
                perror("malloc");
                return;
        }
        new->key = key;

        // just lock critical section
        pthread_mutex_lock(&L->lock);
        new->next = L->head;
        L->head = new;
        pthread_mutex_unlock(&L->lock);
}
```


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Concurrent Linked List: Rewritten (Cont.)

```
(Cont.)
int List_Lookup(list_t *L, int key) {
        int rv = -1;
        pthread_mutex_lock(&L->lock);
        node_t *curr = L->head;
        while (curr) {
                if (curr->key == key) {
                        rv = 0;
                        break;
                }
                curr = curr->next;
        }
        pthread_mutex_unlock(&L->lock);
        return rv; // now both success and failure
}
```


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Scaling Linked List

- Hand-over-hand locking (lock coupling)
  - Add **a lock per node** of the list instead of having a single lock for the entire list.
  - When traversing the list,
    - First grabs the next node's lock.
    - And then releases the current node's lock.
  - Enable a high degree of concurrency in list operations.
    - However, in practice, <u>the overheads of</u> acquiring and releasing locks for each node of a list traversal is *prohibitive*.

Michael and Scott Concurrent Queues

- There are two locks.
  - One for the **head** of the queue.
  - One for the **tail**.
  - The goal of these two locks is to enable concurrency of *enqueue* and *dequeue* operations.

- Add a dummy node
  - Allocated in the queue initialization code
  - Enable the separation of head and tail operations

Concurrent Queues (Cont.)

```c
typedef struct __node_t {
        int value;
        struct __node_t *next;
} node_t;

typedef struct __queue_t {
        node_t *head;
        node_t *tail;
        pthread_mutex_t headLock;
        pthread_mutex_t tailLock;
} queue_t;

void Queue_Init(queue_t *q) {
        node_t *tmp = malloc(sizeof(node_t));
        tmp->next = NULL;
        q->head = q->tail = tmp;
        pthread_mutex_init(&q->headLock, NULL);
        pthread_mutex_init(&q->tailLock, NULL);
}

(Cont.)
```


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Concurrent Queues (Cont.)


```
(Cont.)
    void Queue_Enqueue(queue_t *q, int value) {
        node_t *tmp = malloc(sizeof(node_t));
        assert(tmp != NULL);

        tmp->value = value;
        tmp->next = NULL;

        pthread_mutex_lock(&q->tailLock);
        q->tail->next = tmp;
        q->tail = tmp;
         pthread_mutex_unlock(&q->tailLock);
    }
    int Queue_Dequeue(queue_t *q, int *value) {
        pthread_mutex_lock(&q->headLock);
        node_t *tmp = q->head;
        node_t *newHead = tmp->next;
        if (newHead == NULL) {
            pthread_mutex_unlock(&q->headLock);
            return -1; // queue was empty
        }
        *value = newHead->value;
        q->head = newHead;
        pthread_mutex_unlock(&q->headLock);
        free(tmp);
        return 0;
    }
```

Concurrent Hash Table

- Focus on a simple hash table
  - The hash table does not resize.
  - Built using the concurrent lists
  - It uses a lock per hash bucket each of which is represented by *a list*.

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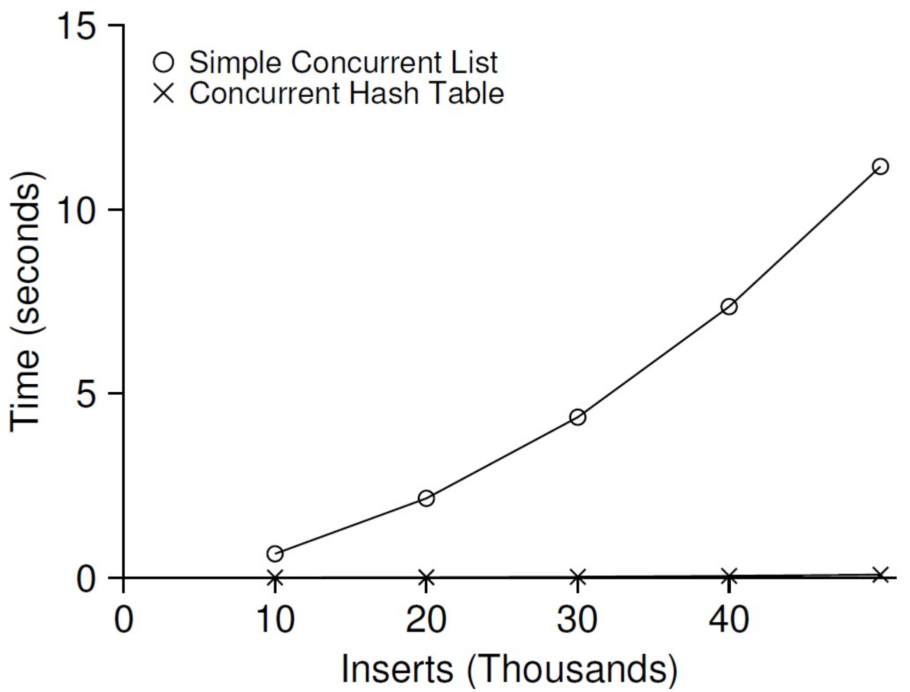
Performance of Concurrent Hash Table

- From 10,000 to 50,000 concurrent updates from each of four threads.
  - iMac with four Intel 2.7GHz i5 CPUs.



The simple concurrent hash table scales magnificently.

Concurrent Hash Table

```
#define BUCKETS (101)

typedef struct __hash_t {
        list_t lists[BUCKETS];
} hash_t;

void Hash_Init(hash_t *H) {
        int i;
        for (i = 0; i < BUCKETS; i++) {
                List_Init(&H->lists[i]);
        }
}

int Hash_Insert(hash_t *H, int key) {
        int bucket = key % BUCKETS;
        return List_Insert(&H->lists[bucket], key);
}

int Hash_Lookup(hash_t *H, int key) {
        int bucket = key % BUCKETS;
        return List_Lookup(&H->lists[bucket], key);
}
```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Module 5: Concurrency & Synchronization
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Condition Variables 条件变量的引入

- There are many cases where a thread wishes to check whether a **condition** is true before continuing its execution. 一个线程需要检查另一个的状态，并据此决定自己是否继续执行
- Example:
  - A parent thread might wish to check whether a child thread has *completed*.
  - This is often called a `join()`.

Condition Variables (Cont.)

A Parent Waiting For Its Child

```
void *child(void *arg) {
    printf("child\n");
    // XXX how to indicate we are done?
    return NULL;
}

int main(int argc, char *argv[]) {
    printf("parent: begin\n");
    pthread_t c;
    Pthread_create(&c, NULL, child, NULL); // create child
    // XXX how to wait for child?
    printf("parent: end\n");
    return 0;
}
```

What we would like to see here is:

```
parent: begin
child
parent: end
```


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Parent waiting fore child: Spin-based Approach

```c
volatile int done = 0;

void *child(void *arg) {
    printf("child\n");
    done = 1;
    return NULL;
}

int main(int argc, char *argv[]) {
    printf("parent: begin\n");
    pthread_t c;
    Pthread_create(&c, NULL, child, NULL); // create child
    while (done == 0)
        ; // spin
    printf("parent: end\n");
    return 0;
}
```

- This is hugely <u>inefficient</u> as the parent spins and **wastes CPU time**.

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How to wait for a condition

- Condition variable 本质上是一个队列及对该队列的操作原语
  - **Waiting** on the condition
    - <u>An explicit queue</u> that threads can put themselves on when some state of execution is not as desired.
  - **Signaling** on the condition
    - Some other thread, *when it changes said state*, can wake one of those waiting threads and allow them to continue.

Definition and Routines

- Declare condition variable

```
pthread cond t c;
```

  - Proper initialization is required.

- Operation (the POSIX calls)

```
pthread_cond_wait(pthread_cond_t *c, pthread_mutex_t *m);    // wait()
pthread_cond_signal(pthread_cond_t *c);                      // signal()
```

  - The wait() call takes a <u>mutex</u> as a parameter.
    - The wait() call release the lock and put the calling thread to sleep.
    - When the thread wakes up, it must re-acquire the lock.

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Parent waiting for Child: Use a condition variable

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

void thr_exit() {
        Pthread_mutex_lock(&m);
        done = 1;
        Pthread_cond_signal(&c);
        Pthread_mutex_unlock(&m);
}

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

void thr_join() {
        Pthread_mutex_lock(&m);
        while (done == 0)
                Pthread_cond_wait(&c, &m);
        Pthread_mutex_unlock(&m);
}

```

Parent waiting for Child: Use a condition variable

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

Create the child thread and continues running itself.

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Parent waiting for Child: Use a condition variable

- **Parent:**
  - Create the child thread and continues running itself.
  - Call into `thr_join()` to wait for the child thread to complete.
    - Acquire the lock
    - Check if the child is done
    - Put itself to sleep by calling `wait()`
    - Release the lock
- **Child:**
  - Print the message “child”
  - Call `thr_exit()` to wake the parent thread
    - Grab the lock
    - Set the state variable `done`
    - Signal the parent thus waking it.

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The importance of the state variable done

```
void thr_exit() {
        Pthread_mutex_lock(&m);
        Pthread_cond_signal(&c);
        Pthread_mutex_unlock(&m);
}

void thr_join() {
        Pthread_mutex_lock(&m);
        Pthread_cond_wait(&c, &m);
        Pthread_mutex_unlock(&m);
}
```

`thr_exit()` and `thr_join()` without variable `done`

- Imagine the case where the *child runs immediately*.
  - The child will signal, but there is <u>no thread asleep</u> on the condition.
  - When the parent runs, it will call wait and be stuck.
  - No thread will ever wake it.

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Another poor implementation

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

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

- The issue here is a subtle **race condition**.
  - The parent calls `thr_join()`.
    - The parent checks the value of `done`.
    - It will see that it is 0 and try to go to sleep.
    - *Just before* it calls wait to go to sleep, the parent is <u>interrupted</u> and the child runs.
  - The child changes the state variable `done` to 1 and signals.
    - But no thread is waiting and thus no thread is woken.
    - When the parent runs again, it sleeps forever.

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The Producer/Consumer (Bound Buffer) Problem

- **Producer**
  - Produce data items
  - Wish to place data items in a buffer
- **Consumer**
  - Grab data items out of the buffer consume them in some way
- Example: Multi-threaded web server
  - *A producer* puts HTTP requests in to a work queue
  - *Consumer threads* take requests out of this queue and process them

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Bounded buffer

- A bounded buffer is used when you pipe the output of one program into another.
  - Example: `grep foo file.txt | wc -l`
    - The `grep` process is the producer.
    - The wc process is the consumer.
    - Between them is an in-kernel bounded buffer.
  - Bounded buffer is Shared resource → **Synchronized access** is required.

The Put and Get Routines (Version 1)

```
int buffer;
int count = 0;          // initially, empty

void put(int value) {
        assert(count == 0);
        count = 1;
        buffer = value;
}

int get() {
        assert(count == 1);
        count = 0;
        return buffer;
}
```

- Only put data into the buffer when `count` is zero.
  - i.e., when the buffer is *empty*.
- Only get data from the buffer when `count` is one.
  - i.e., when the buffer is *full*.

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Producer/Consumer Threads (Version 1)

```c
void *producer(void *arg) {
    int i;
    int loops = (int) arg;
    for (i = 0; i < loops; i++) {
        put(i);
    }
}

void *consumer(void *arg) {
    int i;
    while (1) {
        int tmp = get();
        printf("%d\n", tmp);
    }
}
```

- **Producer** puts an integer into the shared buffer loops number of times.
- **Consumer** gets the data out of that shared buffer.

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Producer/Consumer: Single CV and If Statement

```
cond_t cond;
mutex_t mutex;

void *producer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        Pthread_mutex_lock(&mutex);                 // p1
        if (count == 1)                             // p2
            Pthread_cond_wait(&cond, &mutex);       // p3
        put(i);                                     // p4
        Pthread_cond_signal(&cond);                 // p5
        Pthread_mutex_unlock(&mutex);               // p6
    }
}

void *consumer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        Pthread_mutex_lock(&mutex);                 // c1
        if (count == 0)                             // c2
            Pthread_cond_wait(&cond, &mutex);       // c3
        int tmp = get();                            // c4
        Pthread_cond_signal(&cond);                 // c5
        Pthread_mutex_unlock(&mutex);               // c6
        printf("%d\n", tmp);
    }
}
```

If we have more than one of producer and consumer?

Thread Trace: Broken Solution (Version 1)

	T_{c1}	State	T_{c2}	State	T_p	State	Count	Comment
1	c1	Running		Ready		Ready	0	
2	c2	Running		Ready		Ready	0	
3	c3	Sleep		Ready		Ready	0	Nothing to get
4		Sleep		Ready	p1	Running	0	
5		Sleep		Ready	p2	Running	0	
6		Sleep		Ready	p4	Running	1	Buffer now full
7		Ready		Ready	p5	Running	1	T_{c1} awoken
8		Ready		Ready	p6	Running	1	
9		Ready		Ready	p1	Running	1	
10		Ready		Ready	p2	Running	1	
11		Ready		Ready	p3	Sleep	1	Buffer full; sleep
12		Ready	c1	Running		Sleep	1	T_{c2} sneaks in …
13		Ready	c2	Running		Sleep	1	
14		Ready	c4	Running		Sleep	0	… and grabs data
15		Ready	c5	Running		Ready	0	T_p awoken
16		Ready	c6	Running		Ready	0	
17	c4	Running		Ready		Ready	0	**Oh oh! No data**

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Thread Trace: Broken Solution (Version 1)

- The problem arises for a simple reason:
  - After the producer woke T_{c1}, but before T_{c1} ever ran, the state of the bounded buffer *changed by* T_{c2}.
  - There is no guarantee that when the woken thread runs, the state will still be as desired → Mesa semantics.
    - Virtually every system ever built employs *Mesa semantics*.
  - Hoare semantics provides a stronger guarantee that the woken thread will run immediately upon being woken.

Producer/Consumer: Single CV and While

```
cond_t cond;
mutex_t mutex;

void *producer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        Pthread_mutex_lock(&mutex);                // p1
        while (count == 1)                          // p2
            Pthread_cond_wait(&cond, &mutex);       // p3
        put(i);                                     // p4
        Pthread_cond_signal(&cond);                 // p5
        Pthread_mutex_unlock(&mutex);               // p6
    }
}
void *consumer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        Pthread_mutex_lock(&mutex);                // c1
        while (count == 0)                          // c2
            Pthread_cond_wait(&cond, &mutex);       // c3
        int tmp = get();                            // c4
        Pthread_cond_signal(&cond);                 // c5
        Pthread_mutex_unlock(&mutex);               // c6
        printf("%d\n", tmp);
    }
}
```

Thread Trace: Broken Solution (Version 2)

	T_{c1}	State	T_{c2}	State	T_p	State	Count	Comment
1	c1	Running		Ready		Ready	0	
2	c2	Running		Ready		Ready	0	
3	c3	Sleep		Ready		Ready	0	Nothing to get
4		Sleep	c1	Running		Ready	0	
5		Sleep	c2	Running		Ready	0	
6		Sleep	c3	Sleep		Ready	0	Nothing to get
7		Sleep		Sleep	p1	Running	0	
8		Sleep		Sleep	p2	Running	0	
9		Sleep		Sleep	p4	Running	1	Buffer now full
10		Ready		Sleep	p5	Running	1	T_{c1} awoken
11		Ready		Sleep	p6	Running	1	
12		Ready		Sleep	p1	Running	1	
13		Ready		Sleep	p2	Running	1	
14		Ready		Sleep	p3	Sleep	1	Must sleep (full)
15	c2	Running		Sleep		Sleep	1	Recheck condition
16	c4	Running		Sleep		Sleep	0	T_{c1} grabs data
17	c5	Running		Ready		Sleep	0	Oops! Woke T_{c2}

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Thread Trace: Broken Solution (Version 2) (Cont.)

	T_{c1}	State	T_{c2}	State	T_p	State	Count	Comment
	…	…	…	…	…	…	…	(*cont.*)
18	c6	Running		Ready		Sleep	0	
19	c1	Running		Ready		Sleep	0	
20	c2	Running		Ready		Sleep	0	
21	c3	Sleep		Ready		Sleep	0	Nothing to get
22		Sleep	c2	Running		Sleep	0	
23		Sleep	c3	Sleep		Sleep	0	**Everyone asleep …**

- A consumer should not wake other consumers, only producers, and vice-versa.

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The single Buffer Producer/Consumer Solution

- Use two condition variables and while
  - **Producer** threads wait on the condition `empty`, and signals `fill`.
  - **Consumer** threads wait on `fill` and signal `empty`.

```
cond_t empty, fill;
mutex_t mutex;

void *producer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        Pthread_mutex_lock(&mutex);
        while (count == 1)
            Pthread_cond_wait(&empty, &mutex);
        put(i);
        Pthread_cond_signal(&fill);
        Pthread_mutex_unlock(&mutex);
    }
}
void *consumer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        Pthread_mutex_lock(&mutex);
        while (count == 0)
            Pthread_cond_wait(&fill, &mutex);
        int tmp = get();
        Pthread_cond_signal(&empty);
        Pthread_mutex_unlock(&mutex);
        printf("%d\n", tmp);
    }
}
```

The Final Producer/Consumer Solution

- More **concurrency** and **efficiency** → Add more buffer slots.
  - Allow concurrent production or consuming to take place.
  - Reduce context switches.

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

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

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

The Final Put and Get Routines

The Final Producer/Consumer Solution (Cont.)

```
cond_t empty, fill;
mutex_t mutex;

void *producer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        Pthread_mutex_lock(&mutex);                 // p1
        while (count == MAX)                        // p2
            Pthread_cond_wait(&empty, &mutex);      // p3
        put(i);                                     // p4
        Pthread_cond_signal(&fill);                 // p5
        Pthread_mutex_unlock(&mutex);               // p6
    }
}

void *consumer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        Pthread_mutex_lock(&mutex);                 // c1
        while (count == 0)                          // c2
            Pthread_cond_wait(&fill, &mutex);       // c3
        int tmp = get();                            // c4
        Pthread_cond_signal(&empty);                // c5
        Pthread_mutex_unlock(&mutex);               // c6
        printf("%d\n", tmp);
    }
}
```

Covering Conditions

- Assume there are zero bytes free
  - Thread T_a calls `allocate(100)`.
  - Thread T_b calls `allocate(10)`.
  - Both T_a and T_b wait on the condition and go to sleep.
  - Thread T_c calls `free(50)`.

Which waiting thread should be woken up?

Covering Conditions (Cont.)

```
// how many bytes of the heap are free?
int bytesLeft = MAX_HEAP_SIZE;

// need lock and condition too
cond_t c;
mutex_t m;

void *
allocate(int size) {
    Pthread_mutex_lock(&m);
    while (bytesLeft < size)
        Pthread_cond_wait(&c, &m);
    void *ptr = ...;                  // get mem from heap
    bytesLeft -= size;
    Pthread_mutex_unlock(&m);
    return ptr;
}

void free(void *ptr, int size) {
    Pthread_mutex_lock(&m);
    bytesLeft += size;
    Pthread_cond_signal(&c);          // whom to signal??
    Pthread_mutex_unlock(&m);
}
```

Covering Conditions (Cont.)

- Solution (Suggested by Lampson and Redell)
  - Replace `pthread_cond_signal()` with `pthread_cond_broadcast()`
  - `pthread_cond_broadcast()`
    - Wake up **all waiting threads.**
    - <u>Cost</u>: too many threads might be woken.
    - Threads that shouldn’t be awake will simply wake up, re-check the condition, and then go back to sleep.

Module 5: Concurrency & Synchronization

并发与同步

1. **Concurrency Introduction**
2. **Locks**
3. 基于Lock的并发数据结构
4. Condition Variables 条件变量
5. **Semaphore 信号量**
6. 常见并发问题
7. 基于事件的并发

Semaphore: A definition

- An object with an integer value
  - We can manipulate with two routines; `sem_wait()` and `sem_post()`.
  - Initialization

```
#include <semaphore.h>
sem_t s;
sem_init(&s, 0, 1); // initialize s to the value 1
```

- Declare a semaphore `s` and initialize it to the value 1
- The second argument, 0, indicates that the semaphore is shared between *threads in the same process*.

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Semaphore: wait原语

- `sem_wait()`

```
int sem_wait(sem_t *s) {
    decrement the value of semaphore s by one
    wait if value of semaphore s is negative
}
```

- 减1，若大于0，则返回，否则挂起等待被post唤醒
- If the value of the semaphore was *one* or *higher* when called `sem_wait()`, **return right away**.
- It will cause the caller to suspend execution waiting for a subsequent post.
- When negative, the value of the semaphore is equal to the number of waiting threads.

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Semaphore: post原语

- sem_post()

```
int sem_post(sem_t *s) {
    increment the value of semaphore s by one
    if there are one or more threads waiting, wake one
}
```

- 加1，若有等待线程，则唤醒一个
- Simply **increments** the value of the semaphore.
- If there is a thread waiting to be woken, **wakes** one of them up.

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Binary Semaphores (Locks)

- What should **x** be?
  - The initial value should be **1**.

```
sem_t m;
sem_init(&m, 0, X); // initialize semaphore to X; what should X be?

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


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Thread Trace: Single Thread Using A Semaphore

Value of Semaphore	Thread 0	Thread 1
1		
1	`call sema_wait()`	
0	`sem_wait() returns`	
0	`(crit sect)`	
0	`call sem_post()`	
1	`sem_post() returns`	

Thread Trace: Two Threads Using A Semaphore

Value	Thread 0	State	Thread 1	State
1		Running		Ready
1	call sem_wait()	Running		Ready
0	sem_wait() retruns	Running		Ready
0	(crit set: begin)	Running		Ready
0	*Interrupt; Switch → T1*	Ready		Running
0		Ready	call sem_wait()	Running
-1		Ready	decrement sem	Running
-1		Ready	(sem < 0)→sleep	sleeping
-1		Running	*Switch → T0*	sleeping
-1	(crit sect: end)	Running		sleeping
-1	call sem_post()	Running		sleeping
0	increment sem	Running		sleeping
0	wake(T1)	Running		Ready
0	sem_post() returns	Running		Ready
0	*Interrupt; Switch → T1*	Ready		Running
0		Ready	sem_wait() retruns	Running
0		Ready	(crit sect)	Running
0		Ready	call sem_post()	Running
1		Ready	sem_post() returns	Running

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Semaphores As Condition Variables

```c
sem_t s;

void *
child(void *arg) {
    printf("child\n");
    sem_post(&s); // signal here: child is done
    return NULL;
}

int
main(int argc, char *argv[]) {
    sem_init(&s, 0, X); // what should X be?
    printf("parent: begin\n");
    pthread_t c;
    pthread_create(c, NULL, child, NULL);
    sem_wait(&s); // wait here for child
    printf("parent: end\n");
    return 0;
}
```

A Parent Waiting For Its Child

```
parent: begin
child
parent: end
```

The execution result

- What should **x** be?
  - The value of semaphore should be set to is **0**.

Thread Trace: Parent Waiting For Child (Case 1)

- The parent call `sem_wait()` before the child has called `sem_post()`.

Value	Parent	State	Child	State
0	`Create(Child)`	Running	*(Child exists; is runnable)*	Ready
0	`call sem_wait()`	Running		Ready
-1	`decrement sem`	Running		Ready
-1	`(sem < 0)→sleep`	sleeping		Ready
-1	*Switch→Child*	sleeping	`child runs`	Running
-1		sleeping	`call sem_post()`	Running
0		sleeping	`increment sem`	Running
0		Ready	`wake(Parent)`	Running
0		Ready	`sem_post() returns`	Running
0		Ready	*Interrupt; Switch→Parent*	Ready
0	`sem_wait() retruns`	Running		Ready

Thread Trace: Parent Waiting For Child (Case 2)

- The child runs to completion before the parent call `sem_wait()`.

Value	Parent	State	Child	State
0	`Create(Child)`	Running	*(Child exists; is runnable)*	Ready
0	*`Interrupt; switch→Child`*	Ready	`child runs`	Running
0		Ready	`call sem_post()`	Running
1		Ready	`increment sem`	Running
1		Ready	`wake(nobody)`	Running
1		Ready	`sem_post() returns`	Running
1	`parent runs`	Running	*`Interrupt; Switch→Parent`*	Ready
1	`call sem_wait()`	Running		Ready
0	`decrement sem`	Running		Ready
0	`(sem<0)→awake`	Running		Ready
0	`sem_wait() retruns`	Running		Ready

The Producer/Consumer (Bounded-Buffer) Problem

- **Producer**: `put()` interface
  - Wait for a buffer to become *empty* in order to put data into it.
- **Consumer**: `get()` interface
  - Wait for a buffer to become *filled* before using it.

```c
int buffer[MAX];
int fill = 0;
int use = 0;

void put(int value) {
     buffer[fill] = value;      // line f1
     fill = (fill + 1) % MAX;   // line f2
}

int get() {
     int tmp = buffer[use];     // line g1
     use = (use + 1) % MAX;     // line g2
     return tmp;
}
```


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The Producer/Consumer (Bounded-Buffer) Problem

```c
sem_t empty;
sem_t full;

void *producer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
            sem_wait(&empty);           // line P1
            put(i);                     // line P2
            sem_post(&full);            // line P3
    }
}

void *consumer(void *arg) {
    int i, tmp = 0;
    while (tmp != -1) {
            sem_wait(&full);            // line C1
            tmp = get();                // line C2
            sem_post(&empty);           // line C3
            printf("%d\n", tmp);
    }
}
…
```

First Attempt: Adding the Full and Empty Conditions

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The Producer/Consumer (Bounded-Buffer) Problem

```
int main(int argc, char *argv[]) {
    // …
    sem_init(&empty, 0, MAX);        // MAX buffers are empty to begin with…
    sem_init(&full, 0, 0);           // … and 0 are full
    // …
}
```

First Attempt: Adding the Full and Empty Conditions (Cont.)

- Imagine that `MAX` is greater than 1 .
  - If there are multiple producers, race condition can happen at line *f1*.
  - It means that the old data there is overwritten.
- We've forgotten here is **mutual exclusion**.
  - The filling of a buffer and incrementing of the index into the buffer is a critical section.

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A Solution: Adding Mutual Exclusion

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

void *producer(void *arg) {
     int i;
     for (i = 0; i < loops; i++) {
               sem_wait(&mutex);          // line p0 (NEW LINE)
               sem_wait(&empty);          // line p1
               put(i);                    // line p2
               sem_post(&full);           // line p3
               sem_post(&mutex);          // line p4 (NEW LINE)
     }
}

void *consumer(void *arg) {
     int i;
     for (i = 0; i < loops; i++) {
               sem_wait(&mutex);          // line c0 (NEW LINE)
               sem_wait(&full);           // line c1
               int tmp = get();           // line c2
               sem_post(&empty);          // line c3
               sem_post(&mutex);          // line c4 (NEW LINE)
               printf("%d\n", tmp);
     }
}
```

Adding Mutual Exclusion (Incorrectly)

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A Solution: Adding Mutual Exclusion (Cont.)

- Imagine two thread: one producer and one consumer.
  - The consumer **acquire** the `mutex` (line c0).
  - The consumer **calls** `sem_wait()` on the full semaphore (line c1).
  - The consumer is **blocked** and **yield** the CPU.
    - The consumer still holds the mutex!
  - The producer **calls** `sem_wait()` on the binary `mutex` semaphore (line p0).
  - The producer is now **stuck** waiting too. a classic deadlock.

Finally, A Working Solution

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

void *producer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
            sem_wait(&empty);           // line p1
            sem_wait(&mutex);           // line p1.5 (MOVED MUTEX HERE…)
            put(i);                     // line p2
            sem_post(&mutex);           // line p2.5 (… AND HERE)
            sem_post(&full);            // line p3
    }
}

void *consumer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
            sem_wait(&full);            // line c1
            sem_wait(&mutex);           // line c1.5 (MOVED MUTEX HERE…)
            int tmp = get();            // line c2
            sem_post(&mutex);           // line c2.5 (… AND HERE)
            sem_post(&empty);           // line c3
            printf("%d\n", tmp);
    }
}
```

Adding Mutual Exclusion **(Correctly)**

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Finally, A Working Solution

(Cont.)

```
int main(int argc, char *argv[]) {
    // …
    sem_init(&empty, 0, MAX); // MAX buffers are empty to begin with …
    sem_init(&full, 0, 0);    // ... and 0 are full
    sem_init(&mutex, 0, 1);   // mutex=1 because it is a lock
    // …
}
```


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Reader-Writer Locks

- Imagine a number of concurrent list operations, including **inserts** and simple **lookups**.
  - **insert:**
    - Change the state of the list
    - A traditional critical section makes sense.
  - **lookup:**
    - Simply *read* the data structure.
    - As long as we can guarantee that no insert is on-going, we can allow many lookups to proceed concurrently.

This special type of lock is known as a reader-write lock.

A Reader-Writer Locks

- Only **a single writer** can acquire the lock.
- Once a reader has acquired a read lock,
  - **More readers** will be allowed to acquire the read lock too.
  - A writer will have to wait until all readers are finished.

```
typedef struct _rwlock_t {
    sem_t lock;      // binary semaphore (basic lock)
    sem_t writelock; // used to allow ONE writer or MANY readers
    int readers;     // count of readers reading in critical section
} rwlock_t;

void rwlock_init(rwlock_t *rw) {
    rw->readers = 0;
    sem_init(&rw->lock, 0, 1);
    sem_init(&rw->writelock, 0, 1);
}

void rwlock_acquire_readlock(rwlock_t *rw) {
    sem_wait(&rw->lock);
    …
```


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A Reader-Writer Locks (Cont.)

```
    rw->readers++;
    if (rw->readers == 1)
        sem_wait(&rw->writelock); // first reader acquires 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); // last reader releases writelock
    sem_post(&rw->lock);
}

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

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


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A Reader-Writer Locks (Cont.)

- The reader-writer locks have fairness problem.
  - It would be relatively easy for reader to **starve writer**.
  - How to prevent more readers from entering the lock once a writer is waiting?

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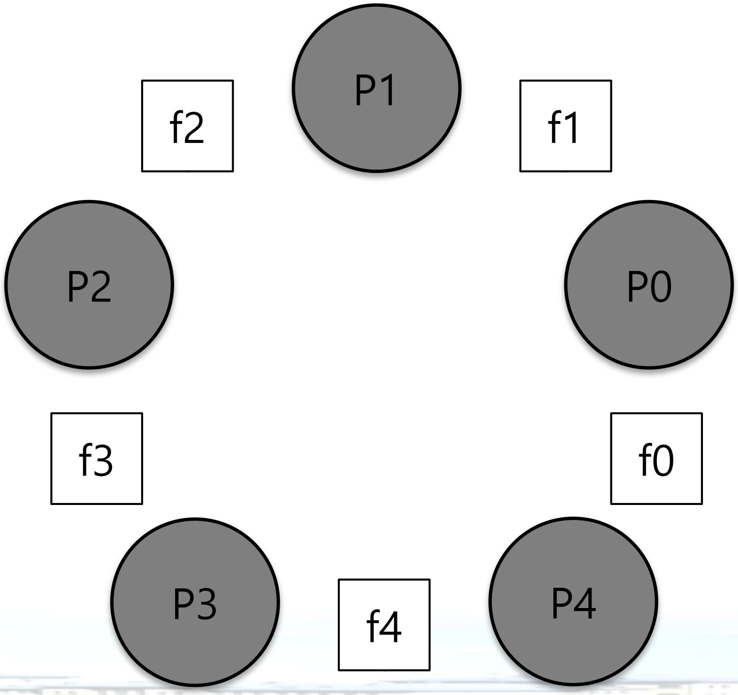
The Dining Philosophers

- Assume there are five “**philosophers**” sitting around a table.
  - Between each pair of philosophers is <u>a single fork</u> (five total).
  - The philosophers each have times where they **think**, and don’t need any forks, and times where they **eat**.
  - In order to *eat*, a philosopher needs two forks, both the one on their *left* and the one on their *right*.
  - **The contention for these forks.**



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The Dining Philosophers (Cont.)

- Key challenge
  - There is **no deadlock**.
  - **No** philosopher **starves** and never gets to eat.
  - **Concurrency** is high.

```
while (1) {
        think();
        getforks();
        eat();
        putforks();
}
```

Basic loop of each philosopher

```
// helper functions
int left(int p) { return p; }

int right(int p) {
        return (p + 1) % 5;
}
```

Helper functions (Downey's solutions)

- Philosopher `p` wishes to refer to the fork on their left → call `left(p)`.
- Philosopher `p` wishes to refer to the fork on their right → call `right(p)`.

The Dining Philosophers (Cont.)

- We need some **semaphore**, one for each fork: `sem_t forks[5]`.

```
void getforks() {
    sem_wait(forks[left(p)]);
    sem_wait(forks[right(p)]);
}

void putforks() {
    sem_post(forks[left(p)]);
    sem_post(forks[right(p)]);
}
```

The `getforks()` and `putforks()` Routines (Broken Solution)

- Deadlock occur!
  - If each philosopher happens to **grab the fork on their left** before any philosopher can grab the fork on their right.
  - Each will be stuck *holding one fork* and waiting for another, *forever*.

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A Solution: Breaking The Dependency

- Change how forks are acquired.
  - Let’s assume that philosopher 4 acquire the forks in a *different order*.

```
void getforks() {
    if (p == 4) {
            sem_wait(forks[right(p)]);
            sem_wait(forks[left(p)]);
    } else {
            sem_wait(forks[left(p)]);
            sem_wait(forks[right(p)]);
    }
}
```

- There is no situation where each philosopher grabs one fork and is stuck waiting for another. **The cycle of waiting is broken**.

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How To Implement Semaphores

- Build our own version of semaphores called Zemaphores

```
typedef struct __Zem_t {
    int value;
    pthread_cond_t cond;
    pthread_mutex_t lock;
} Zem_t;

// only one thread can call this
void Zem_init(Zem_t *s, int value) {
    s->value = value;
    Cond_init(&s->cond);
    Mutex_init(&s->lock);
}

void Zem_wait(Zem_t *s) {
    Mutex_lock(&s->lock);
    while (s->value <= 0)
    Cond_wait(&s->cond, &s->lock);
    s->value--;
    Mutex_unlock(&s->lock);
}

void Zem_post(Zem_t *s) {
    Mutex_lock(&s->lock);
    s->value++;
    Cond_signal(&s->cond);
    Mutex_unlock(&s->lock);
}
```


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How To Implement Semaphores (Cont.)

- Zemaphore don't maintain the invariant that *the value of* the semaphore.
  - The value never be lower than zero.
  - This behavior is **easier** to implement and **matches** the current Linux implementation.

例题

【例题】当 V 操作唤醒一个等待进程时，被唤醒进程变为（ ）态。

A. 运行

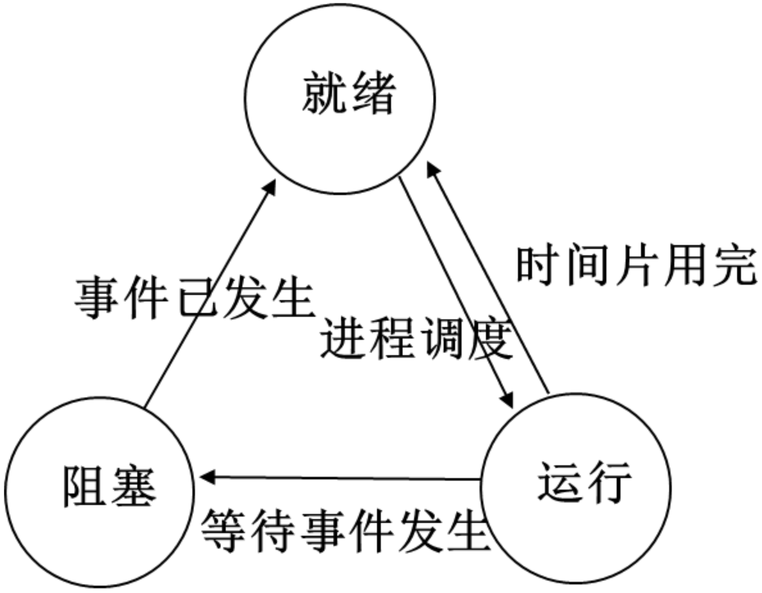
B. 阻塞

C. 就绪

D. 完成

答案：C

等待唤醒的进程处于阻塞态，被唤醒后进入就绪态。只有就绪进程能获得处理器资源，被唤醒的进程并不能直接转化为运行态。



进程:状态转换

例题

【例题】有三个进程共享同一程序段，而每次只允许两个进程进入该程序段，若用 PV 操作同步机制，则信号量 S 的取值范围是（ ）

A. 2,1,0,-1

B. 3,2,1,0

C. 2,1,0,-1,-2

D. 1,0,-1,-2

答案：A

因为每次允许两个进程进入该程序段，信号量最大值取2（否则三个进程可以同时进入程序段）。至多有三个进程申请，则信号量最小为-1。

例题

【2013统考真题】某博物馆最多可容纳500人同时参观，有一个出入口，该出入口一次仅允许一人通过，参观者的活动描述如下：

```
cobegin
        参观者进程i;
        {
                ...
                进门;
                ...
                参观;
                ...
                出门;
                ...
        }
coend
```

请添加必要的信号量和 P，V[或 wait()，signal()]操作，以实现上述过程中的互斥与同步。要求写出完整的过程，说明信号量的含义并赋值。

例题

解答：

出入口一次仅允许一个人通过，设置互斥信号量mutex，初值为1。博物馆最多可同时容纳500人，因此设置信号量empty，初值为500。

```
Semaphore empty = 500; // 博物馆可以容纳的最多人数
Semaphore mutex = 1; // 用于出入口资源的控制
cobegin
参观者进程i:
{
    …
    P(empty); // 可容纳人数减1
    P(mutex); // 互斥使用门
    进门;
    V(mutex);
    参观;
    P(mutex); // 互斥使用门
    出门;
    V(mutex);
    V(empty); // 可容纳人数增加1
    …
}
coend
```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例题

【2011统考真题】某银行提供1个服务窗口和10个供顾客等待的座位。顾客到达银行时，若有空座位，则到取号机上领取一个号，等待叫号。取号机每次仅允许一位顾客使用。当营业员空闲时，通过叫号选取一位顾客，并为其服务。顾客和营业员的活动过程描述如下：

```
cobegin
{
    process 顾客i
    {
        从取号机获取一个号码;
        等待叫号;
        获取服务;
    }
}
{
    process 营业员
    {
        while(TRUE)
        {
            叫号;
            为顾客服务;
        }
    }
}
coend
```

请添加必要的信号量和 P，V[或 wait()，signal()]操作，实现上述过程中的互斥与同步。要求写出完整的过程，说明信号量的含义并赋值。

例题

解答：
互斥资源：取号机（一次只有一位顾客领号），因此设置互斥信号量mutex。
同步问题：顾客需要获得空座位等待叫号。营业员空闲时，将选取一位顾客并为其服务。是否有空座位影响等待顾客的数量，是否有顾客决定了营业员是否能开始服务，因此分别设置信号量empty和full来实现这一同步关系。
另外，顾客获得空座位后，需要等待叫号和被服务。顾客与营业员就服务何时开始又构成了一个同步关系，定义信号量service来完成这一同步过程。

```
semaphore empty = 10; // 空座位数量
semaphore full = 0; // 已占座位的数量
semaphore mutex = 1; // 互斥使用取号机
semaphore service = 0; // 等待叫号（当前是否正在服务）

cobegin
{
    Process 顾客 i{
        P(empty); // 等空位
        P(mutex); // 申请使用取号机
        取号;
        V(mutex); // 取号结束
        V(full); // 通知营业员有新顾客
        P(service); // 等待营业员叫号
        接收服务
    }
}
{
    Process 营业员{
        while(True){
            P(full); // 没有顾客则休息
            V(empty); // 离开座位
            V(service); // 叫号
            为顾客服务;
        }
    }
}
coend
```

信号量问题解题步骤

1. 找出问题中所有同步与互斥的关系

- 互斥
  - 找到进程竞争的临界资源
  - 抓住“仅允许”或类似词汇
  - 博物馆出入口每次仅允许一人通过、取号机每次仅允许一位顾客使用
- 同步
  - 不同进程对资源合作处理
  - 博物馆内容纳500人、空座位10个

2. 确定信号量个数及每个信号量的初值

- 互斥
  - 用1个信号量，代表资源是否被互斥使用
  - 一般初值为0或1
- 同步
  - 用1或2个信号量，1个信号量用于判断是否资源为empty或full，2个信号量分别判断资源是否为empty和full
  - 一般初值为题目中给出的特定数值（容纳500人、空座位10个）或0

3. 用类似程序的语言描述算法

Module 5: Concurrency & Synchronization
并发与同步

1. Concurrency Introduction
2. **Locks**
3. **基于Lock的并发数据结构**
4. Condition Variables 条件变量
5. Semaphore 信号量
6. **常见并发问题**
7. 基于事件的并发

Common Concurrency Problems

- More recent work focuses on studying other types of common concurrency bugs. 而不是deadlock
  - Take a brief look at some example concurrency problems found in real code bases.

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What Types Of Bugs Exist?

- Focus on four major open-source applications
  - MySQL, Apache, Mozilla, OpenOffice.

Application	What it does	Non-Deadlock	Deadlock
MySQL	Database Server	14	9
Apache	Web Server	13	4
Mozilla	Web Browser	41	16
Open Office	Office Suite	6	2
Total		**74**	**31**

Bugs In Modern Applications

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Non-Deadlock Bugs

- Make up a majority of concurrency bugs.
- Two major types of non deadlock bugs:
  - Atomicity violation 违反原子性
  - Order violation 违反顺序性

Atomicity-Violation Bugs

- The desired **serializability** among multiple memory accesses is *violated*.
  - Simple Example found in MySQL:
    - Two different threads access the field `proc_info` in the `struct thd`.

```
Thread1::
if(thd->proc_info){
   …
   fputs(thd->proc_info , …);
   …
}

Thread2::
thd->proc_info = NULL;
```


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Atomicity-Violation Bugs (Cont.)

- **Solution**: Simply add locks around the shared-variable references.

```
pthread_mutex_t lock = PTHREAD_MUTEX_INITIALIZER;

Thread1::
pthread_mutex_lock(&lock);
if(thd->proc_info){
    …
    fputs(thd->proc_info , …);
    …
}
pthread_mutex_unlock(&lock);

Thread2::
pthread_mutex_lock(&lock);
thd->proc_info = NULL;
pthread_mutex_unlock(&lock);
```


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Order-Violation Bugs

- The desired order between two memory accesses is flipped.
  - i.e., **A** should always be executed before **B**, but the order is not enforced during execution.
  - **Example**:

```
Thread1::
void init(){
     mThread = PR_CreateThread(mMain, …);
}

Thread2::
void mMain(…){
     mState = mThread->State
}
```

- The code in Thread2 seems to assume that the variable `mThread` has already been *initialized* (and is not `NULL`).

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Order-Violation Bugs (Cont.)

- **Solution**: Enforce ordering using condition variables

```
pthread_mutex_t mtLock = PTHREAD_MUTEX_INITIALIZER;
pthread_cond_t mtCond = PTHREAD_COND_INITIALIZER;
int mtInit = 0;

Thread 1::
void init(){
    …
    mThread = PR_CreateThread(mMain,…);

    // signal that the thread has been created.
    pthread_mutex_lock(&mtLock);
    mtInit = 1;
    pthread_cond_signal(&mtCond);
    pthread_mutex_unlock(&mtLock);
    …
}

Thread2::
void mMain(…){
    …
```


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Order-Violation Bugs (Cont.)

```
    // wait for the thread to be initialized …
    pthread_mutex_lock(&mtLock);
    while(mtInit == 0)
        pthread_cond_wait(&mtCond, &mtLock);
    pthread_mutex_unlock(&mtLock);

    mState = mThread->State;
    …
}
```


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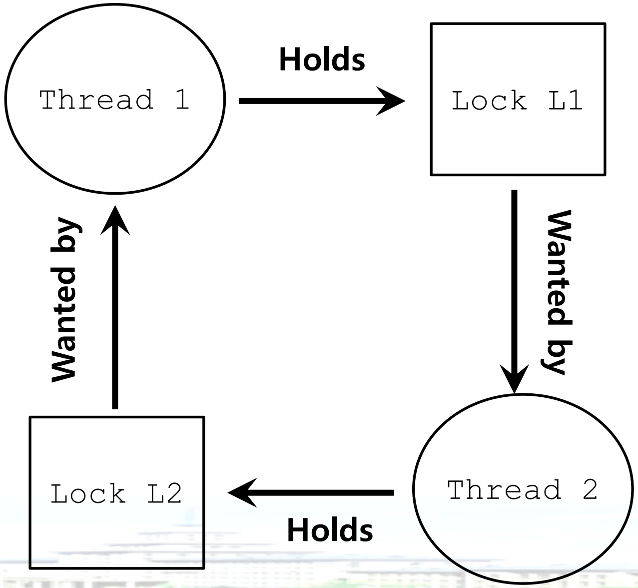
Deadlock Bugs

```
Thread 1:          Thread 2:
lock(L1);          lock(L2);
lock(L2);          lock(L1);
```

- The presence of a cycle
  - Thread1 is holding a lock L1 and waiting for another one, L2.
  - Thread2 that holds lock L2 is waiting for L1 to be release.



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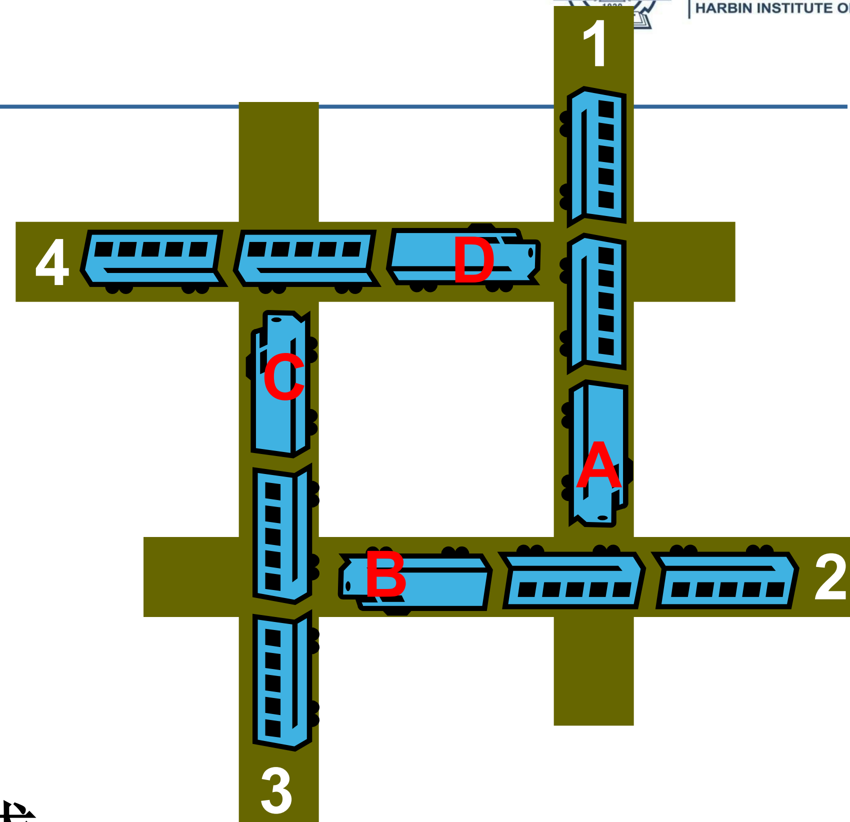
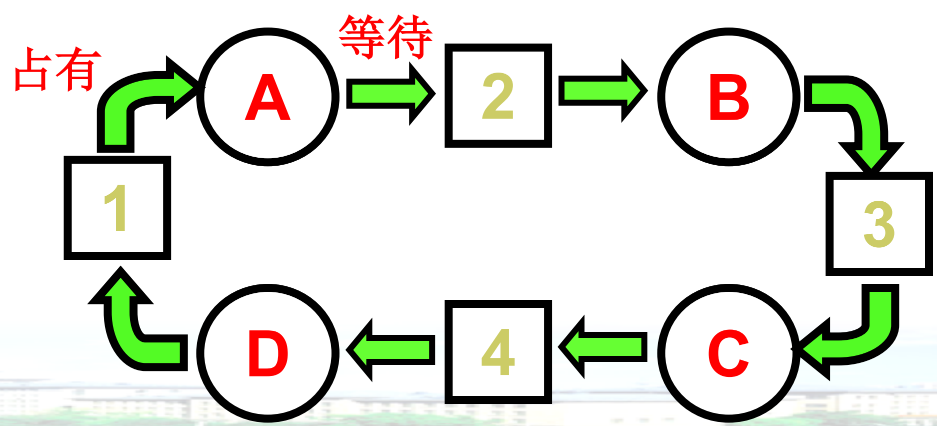
死锁现象

- 看一个实际的例子

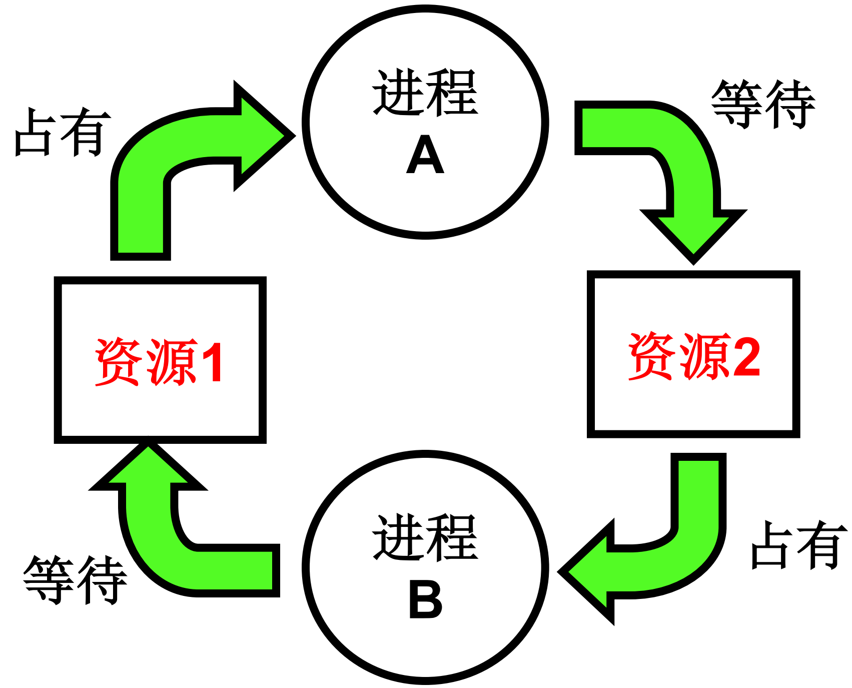


- 现在分析这个例子
  - 竞争使用资源: 道路
  - A占有道路1，又要请求道路2，B占有...
  - 形成了无限等待



死锁概念(Deadlock)

- 死锁: 多个进程（线程）因循环等待资源而造成无法执行的现象。



  - 死锁会造成进程（线程）无法执行
  - 死锁会造成系统资源的极大浪费(资源无法释放)

例题

【例题】某计算机系统中有 8 台打印机，由 K 个进程竞争使用，每个进程最多需要 3 台打印机。该系统可能发生死锁的 K 的最小值是（　）。

A．2

B．3

C．4

D．5

答案：C

考虑最极端情况，因为每个进程最多需要3台打印机，若每个进程已经占有了2台打印机，则只要还有多的打印机，总能满足一个进程达到3台的条件，然后顺利执行。所以将8台打印机分给 K 个进程，每个进程有2台打印机，这就是极端情况，K = 4。

死锁特征分析—产生死锁的四个必要条件

- 多个进程因等待资源才造成死锁
- 资源: 进程在完成其任务过程所需要的所有对象
  - CPU、内存、磁盘块、外设、文件、信号量 …
- 显然有些资源不会造成死锁，而有些会
  - 只读文件是不会造成进程等待的，也就不会死锁
  - 打印机一次只能让一个进程使用，就会造成死锁

称为互斥访问资源

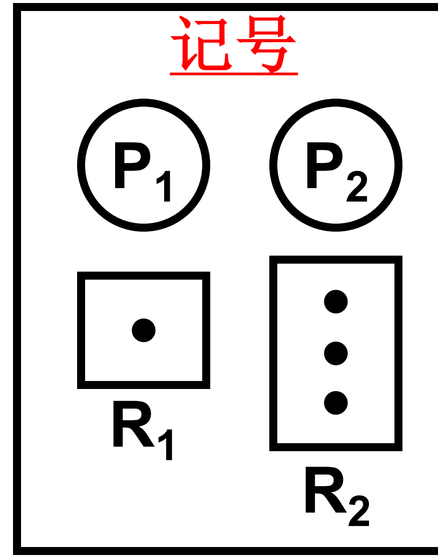
  - 显然，资源互斥访问是死锁的必要条件

- 资源请求需要形成环路等待才死锁！如何描述这种等待关系?

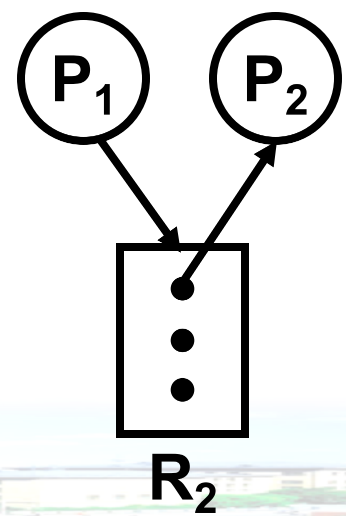
资源分配图

资源分配图模型

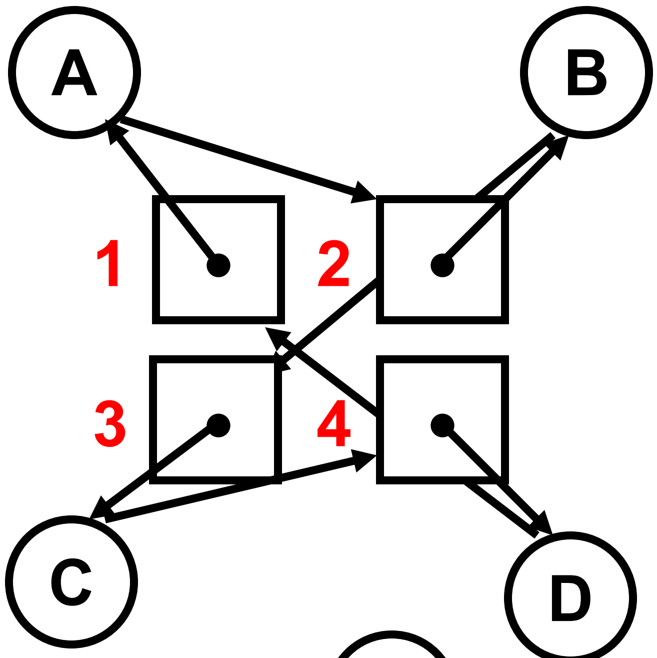
- 一个进程集合$\{P_1,P_2,\ldots,P_n\}$
- 一资源类型集合$\{R_1,R_2,\ldots,R_m\}$
- 资源类型R_i有W_i个实例

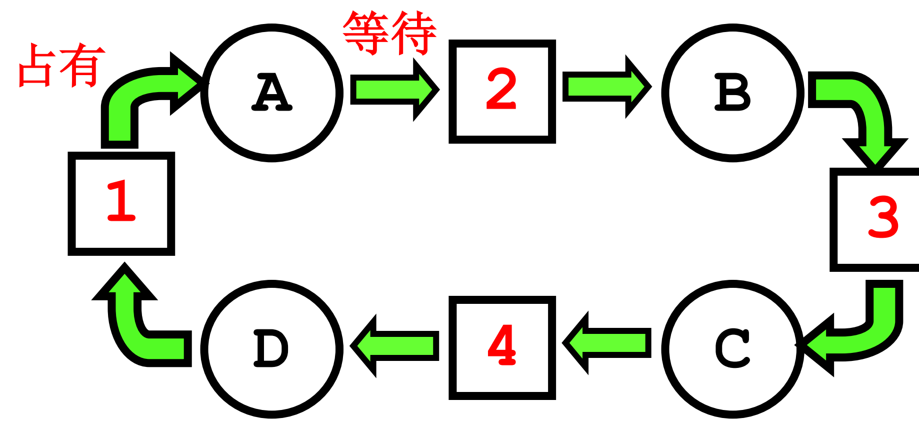


- 资源请求边：有向边$P_i \rightarrow R_j$
- 资源分配边：有向边$R_i \rightarrow P_k$



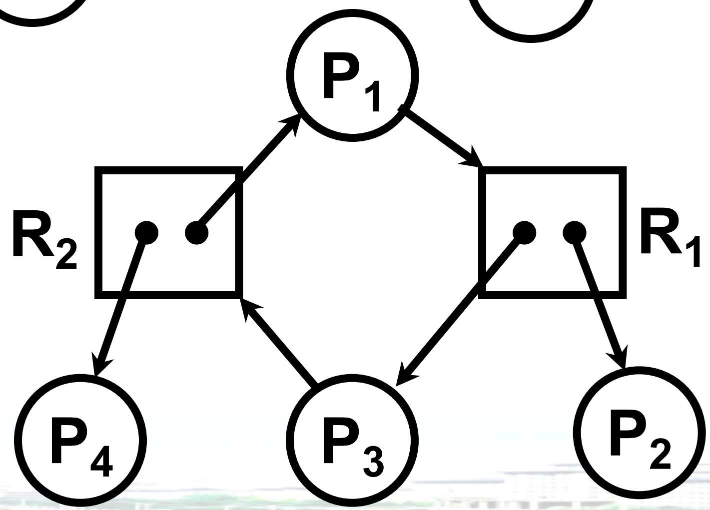
资源分配图实例





- 存在环路:

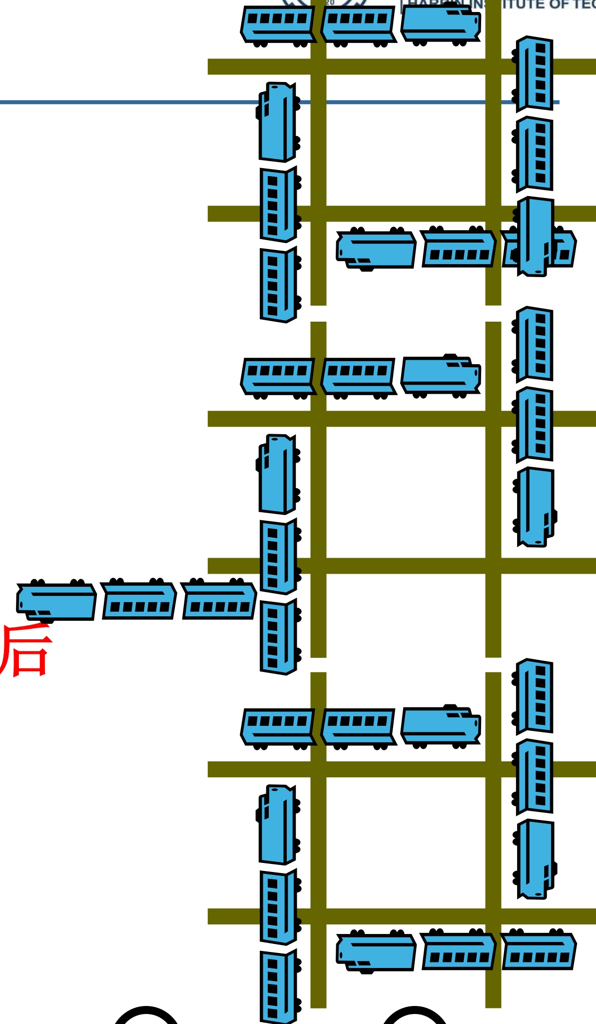
  1→A→2→B→3→C→4→D→1
- 产生死锁



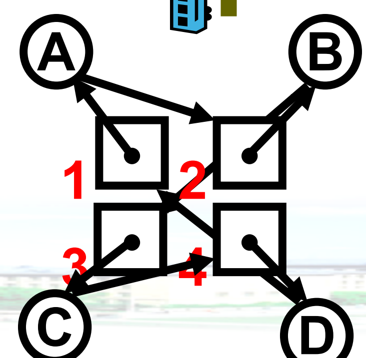
- 存在环路:

  $P_1 \rightarrow R_1 \rightarrow P_3 \rightarrow R_2 \rightarrow P_1$
- 但并不死锁，仍可继续执行

死锁的4个必要条件



- 互斥使用(Mutual exclusion)
  - 至少有一个资源互斥使用
- 不可抢占(No preemption)
  - 资源只能自愿放弃，如车开走以后
- 请求和保持(Hold and wait)
  - 进程必须占有资源，再去申请
- 循环等待(Circular wait)
  - 在资源分配图中存在一个环路



Conditional for Deadlock

- Four conditions need to hold for a deadlock to occur.

Condition	Description
Mutual Exclusion	**Threads claim exclusive control of resources that they require.**
Hold-and-wait	**Threads hold resources allocated to them while waiting for additional resources**
No preemption	**Resources cannot be forcibly removed from threads that are holding them.**
Circular wait	**There exists a circular chain of threads such that each thread holds one more resources that are being requested by the next thread in the chain**

- If any of these four conditions are not met, **deadlock cannot occur**.

死锁处理方法概述

- 死锁预防　“no smoking”，预防火灾
  - 破坏死锁的必要条件
- 死锁避免　检测到煤气超标时，自动切断电源
  - 检测每个资源请求，如果造成死锁就拒绝
- 死锁检测+恢复　发现火灾时，立刻拿起灭火器
  - 检测到死锁出现时，剥夺一些进程的资源
- 死锁忽略　在太阳上可以对火灾全然不顾
  - 就好像没有出现死锁一样

死锁预防: 破除死锁的必要条件之(1)(2)

- 破坏互斥使用
  - 资源的固有特性，通常无法破除，如打印机
- 破除不可抢占
  - 如果一个进程占有资源并申请另一个不能立即分配的资源，那么已分配资源就可被抢占（即持有不用即可抢占）
  - 如果申请的资源得到满足，则抢占其他资源一次性分配给该进程
  - 只对状态能保存和恢复的资源(如CPU，内存空间)有效，对打印机等外设不适用

实例：两个进程使用串口，都要读串口，数据不同不可恢复。

死锁预防: 破除死锁的必要条件之(3)

- 破除请求和保持
  - 在进程执行前，一次性申请所有需要的资源
  - 缺点1: 需要预知未来，编程困难
  - 缺点2: 许多资源分配后很长时间后才使用，资源利用率低

死锁预防: 破除死锁的必要条件之(4)

- 破除循环等待
  - 对资源类型进行排序，资源申请必须按序进行
  - 例如：所有的进程必须先申请磁盘驱动，再申请打印机，再....，如同日常交通中的单行道
  - 缺点: 如果编程时就需考虑，用户会觉得很别扭；可能需要释放某些资源(申请序号小的资源)，进程可能会无法执行
- 总之，破除死锁的必要条件会引入不合理因素，实际中很少使用。

死锁避免

不死锁就成了问题的核心!

- 思想: 判断此次请求是否造成死锁
  若会造成死锁，则拒绝该请求

- 安全状态定义：如果系统中的所有进程存在一个可完成的执行序列P_1，…P_n，则称系统处于安全状态

都能执行完成当然就不死锁

- 安全序列：上面的执行序列P_1，…P_n

如何找到这样的序列?

死锁避免之银行家算法

一个银行家：目前手里只有1亿

第A个开发商：已贷款15亿，资金紧张还需3亿。

第B个开发商：已贷款5亿，还需贷款1亿，运转良好能收回。

第C个开发商：已贷款2亿，欲贷款18亿

… …

开发商B还钱，再借给A，则可以继续借给C

银行家当前可用的资金（Available）？可以利用的资金，即可用的加上能收回的共有多少（work）？各个开发商已贷款——已分配的资金（Allocation）？各个开发商还需要贷款（need）

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死锁避免之银行家算法

- 安全序列P_1，…P_n应该满足的性质：

Pi(1≤i≤n)需要资源 ≤ 剩余资源 + 分配给Pj(1≤j<i)资源

```
Banker()
int n,m; //系统中进程总数n和资源种类总数m
int Available[m]; //资源当前可用总量
int Allocation[n][m];
      //当前给分配给每个进程的各种资源数量
int Need[n][m];
      //当前每个进程还需分配的各种资源数量
int Work[m]; //当前可分配的资源，包括可收回的
bool Finish[n]; //进程是否结束
```

死锁避免之银行家算法

- 安全状态判定（思路）：

①初始化设定：

Work = Available（*动态记录当前可（收回）分配资源*）

Finish[i]=false（*设定所有进程均未完成*）

②查找这样的进程P_i（*未完成但目前剩余资源可满足其需要，这样的进程是能够完成的*）：

a）Finish[i] = =false　　　b）Need[i] ≤ Work

如果没有这样的进程P_i，则跳转到第④步

③（*若有则*）P_i一定能完成，并归还其占用的资源，即：

a）Finish[i] = true　　　b）Work = Work +Allocation[i]

GOTO 第②步，继续查找

④如果所有进程P_i都是能完成的，即Finish[i]=ture

则系统处于*安全状态*，否则系统处于*不安全状态*

死锁避免之银行家算法实例

- 当前状态:

	Allocation A B C	Need A B C	Available A B C
~~P0~~	~~0 1 0~~	~~7 4 3~~	3 3 2
~~P1~~	~~2 0 0~~	~~1 2 2~~	
~~P2~~	~~3 0 2~~	~~6 0 0~~	
~~P3~~	~~2 1 1~~	~~0 1 1~~	
~~P4~~	~~0 0 2~~	~~4 3 1~~	

Work=[3 3 2]

P_1 Work=[5 3 2]

P_3 Work=[7 4 3]

P_4 Work=[7 4 5]

P_0 Work=[7 5 5]

P_2 Work=[10 5 7]

- 安全序列是<P_1, P_3, P_4, P_0 ,P_2>
- 安全序列是唯一的吗？

死锁避免之银行家算法

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```
bool Found;
Work = Available; Finish = false;
while(true){
    Found = false; //是否为安全序列找到一个新进程
    for(i=1; i<=n; i++){
      if(Finish[i]==false && Need[i]<=Work){
         Work = Work + Allocation[i];
         Finish[i] = true;
         printf("%d->",i);//输出安全序列
         Found = true;
      }
    } 没有安全序列或已经找到
    if(Found==false)break;
}
for(i=1;i<=n;i++)
    if(Finish[i]==false)
      return "deadlock";
```

$T(n)=O(mn^2)$

最好情形：安全状态就是P_1-P_n

最坏情形：P_n-P_1

死锁避免之资源请求算法

思想：可用的资源可以满足某个进程的资源请求，则分配，然后寻找安全序列，找到，分配成功，找不到，已分配资源收回。

```
extern Banker();
int Request[m]; /*进程Pi的资源申请*/
if(Request>Need[i]) return “error”;
if(Request>Available) sleep();
Available=Available-Request;
Allocation[i]=Allocation[i]+Request;
Need[i]=Need[i]-Request;
                /*先将资源分配给Pi*/
if(Banker()=="deadlock")
          /*调用银行家算法判定是否会死锁*/
   拒绝Request;/*若算法判定deadlock则拒绝请求, 资源回滚*/
```

死锁避免之资源请求实例(1)

- P_1申请资源(1,0,2)

	Allocation	Need	Available
	A B C	A B C	A B C
P0	0 1 0	7 4 3	2 3 0
P1	3 0 2	0 2 0	
P2	3 0 2	6 0 0	
P3	2 1 1	0 1 1	
P4	0 0 2	4 3 1	

	Allocation	Need	Available
	A B C	A B C	A B C
P0	0 1 0	7 4 3	3 3 2
P1	2 0 0	1 2 2	
P2	3 0 2	6 0 0	
P3	2 1 1	0 1 1	
P4	0 0 2	4 3 1	

- 序列<P_1, P_3, P_2, P_4, P_0>是安全的
- 此次申请允许

死锁避免之资源请求实例(2)

- P_0再申请(0,2,0)

	Allocation	Need	Available
	A B C	A B C	A B C
P0	0 3 0	7 2 3	2 1 0
P1	3 0 2	0 2 0	
P2	3 0 2	6 0 0	
P3	2 1 1	0 1 1	
P4	0 0 2	4 3 1	

	Allocation	Need	Available
	A B C	A B C	A B C
P0	0 1 0	7 4 3	2 3 0
P1	3 0 2	0 2 0	
P2	3 0 2	6 0 0	
P3	2 1 1	0 1 1	
P4	0 0 2	4 3 1	

- 进程P_0, P_1, P_2, P_3, P_4一个也没法执行，死锁进程组
- 此次申请被拒绝

银行家算法讨论:

- 每个进程进入系统时必须告知所需资源的最大数量
  对应用程序员要求高
- 安全序列寻找算法（安全状态判定算法）计算时间复杂度为$O(mn^2)$，过于复杂
- 若每次资源请求都要调用银行家算法，耗时过大，系统效率降低
- 采用此算法，存在情况：当前有资源可用，尽管可能很快就会释放，由于会使整体进程处于不安全状态，而不被分配，致使资源利用率大大降低

死锁检测+恢复：死锁检测

- 基本原因：每次申请都执行$O(mn^2)$，效率低
- 对策：只要可用资源足够，则分配，发现问题再处理
  - 定时检测或者当发现资源利用率低时检测

//对银行家算法进行改进

```
bool Found;
int Request[n][m];
Work = Available; Finish = false;
if Allocation[i] != 0: Finish[i] = false;
else: Finish[i] = true;
while(true){
    Found = false; //是否为安全序列找到一个新进程
    for(i=1; i<=n; i++){
      if(Finish[i]==false && Request[i]<=Work){
           Work = Work + Allocation[i];
           Finish[i] = true;
           Found = true;
      }
    }
    if(Found==false)break;
}
for(i=1;i<=n;i++) {
    if(Finish[i]==false) {
      deadlock = deadlock + {i}; return “deadlock”;
    }
}
```

对于无分配资源的进程，不论其是否获得请求资源，则认为其是完成的

死锁检测+恢复：死锁恢复

- 终止进程　选谁终止?
  - 优先级? 占用资源多的? …
- 剥夺资源　进程需要回滚 (rollback)
  - 回滚点的选取? 如何回滚? …

鸵鸟算法(死锁忽略)

- 死锁预防?
  - 引入太多不合理因素…
- 死锁避免?
  - 每次申请都执行银行家算法$O(mn^2)$，效率太低
- 死锁检测+恢复?
  - 还要执行银行家算法$O(mn^2)$，且恢复并不容易
- 鸵鸟算法: 对死锁不做任何处理……
  - 死锁出现时，手动干预——重新启动
  - 死锁出现不是确定的，避免死锁付出的代价毫无意义
  - 有趣的是大多数操作系统都用它，如**UNIX**和**Windows**

死锁总结

- 进程竞争资源 ⇒ 有可能形成循环竞争 ⇒ 死锁
- 死锁需要处理 ⇒ 死锁分析 ⇒ 死锁的必要条件
- 死锁处理 ⇒ 预防、避免、检测+恢复、忽略
- 死锁预防: 破除必要条件 ⇒ 引入了不合理因素
- 死锁避免: 用银行家算法找安全序列 ⇒ 效率太低
- 死锁检测恢复: 银行家算法找死锁进程组并恢复 ⇒ 实现较难
- 死锁忽略: 就好像没有死锁 ⇒ 现在用的最多

任何思想、概念、技术的主流都会
随着时间而改变，操作系统尤为明显!

例题

【例题】在下列死锁的解决方法中，属于死锁预防策略的是（　）。

A. 银行家算法

B. 资源有序分配算法

C. 死锁检测算法

D. 资源分配图化简算法

答案：B

A.　属于**死锁避免**

B.　破坏了循环等待，**破坏死锁的必要条件**属于死锁预防

C.　属于**死锁检测**

D.　属于**死锁检测**

谢 谢 ！