TCSS 422: OPERATING SYSTEMS

Proportional Share Scheduling, Linux Completely Fair Scheduler, Introduction to Concurrency

Wes J. Lloyd
School of Engineering and Technology
University of Washington - Tacoma

FEEDBACK FROM 1/23

- **What are batch jobs?**
- "Batch jobs" originates from the legacy concept of "batch processing" in computer systems
- Batch processing involves scripted running of one or more programs that run sequentially with no human interaction
- Examples include general data processing, system "housekeeping" tasks, report generation
- Tasks may be high-volume and repetitive
- Batch jobs are long-running tasks where most of the execution time requires long interrupted access to run code on the CPU

FEEDBACK - 2

- **How does MLFQ priority switching work again?**
- **Rule 3:** When a job enters the system, it is placed at the highest priority.
- **Rule 4:** Once a job uses up its time allotment at a given level (regardless of how many times it has given up the CPU), its priority is reduced (i.e., it moves down on queue).
  - Address ***gaming the scheduler*** through job accounting to track to execution time
- **Rule 5:** After some time period S, move all the jobs in the system to the topmost queue.
  - ***Priority boost***

FEEDBACK - 3

- **Is priority for processes scheduled using the MLFQ scheduler determined solely based on use of a time quantum (for each queue)?**
- For the classic MLFQ described in Ch. 8: **YES**
- For actual implementations of MLFQ, priority (which queue a job is in) could be influenced by the job's nice value

FEEDBACK: *EXPLAIN THE SECOND EXAMPLE AGAIN*

- Given a system with a quantum length of 10 ms in its highest queue, how often would you have to boost jobs back to the highest priority level to **guarantee** that a single long-running (and potentially starving) job (let's say ***Job A***) gets at least 5% of the CPU?
- Key is: "***guarantee***" and "***starving***" → assume worst case scenario
- "***Single long-running***" → implies "BATCH" job
- WORST CASE: some combination of n short jobs consumes ***all*** remaining time of the 10ms quantum without relinquishing the CPU
  - 2 jobs=5ms ea; 3 jobs=3.33ms ea;.. ****does it matter how many jobs?****
  - **The quantum is gone!** *n jobs* ***ALWAYS*** *uses full time quantum (10 ms)*
  - Batch job A starts, runs for full quantum of 10ms
  - If 10ms is 5% of the CPU, when must the priority boost be ???
  - **ANSWER** → ***Priority boost should occur every 200ms***

FEEDBACK - 5

- **I'm confused about how to do a scheduling graph.**
- From the in class example, at T=3 C disappears
  - Where does it go?
- Then there are two A's
  - When do letters repeat?

Jackson deploys a 3-level MLFQ scheduler. The time slice is 1 for high priority jobs, 2 for medium priority, and 4 for low priority. This MLFQ scheduler performs a Priority Boost every 6 timer units. When the priority boost fires, the current job is preempted, and the next scheduled job is run in round-robin order.

Job	Arrival Time	Job Length
A	T=0	4
B	T=0	16
C	T=0	8

(11 points) Show a scheduling graph for the MLFQ scheduler for the jobs above. Draw vertical lines for key events and be sure to label the X-axis times as in the example. Please draw clearly. An unreadable graph will loose points.

HIGH |
MED |
LOW |
0

OBJECTIVES

- Quiz 2: Chapter 7 Schedulers
- Assignment 0 / Linux Tutorial
- C Tutorial
- Assignment 1 Posted
- **CPU Scheduling:**
- Chapter 9 – Proportional Share Scheduler
  Linux Completely Fair Scheduler (CFS)
- **Parallel programming with P-threads:**
- Chapter 26 – Intro to concurrency
- Chapter 27 – Linux Thread API
- Chapter 28 – Intro to locks

CHAPTER 9 - PROPORTIONAL SHARE SCHEDULER

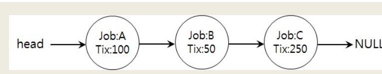
PROPORTIONAL SHARE SCHEDULER

- Also called fair-share scheduler
  or lottery scheduler
  - Guarantees each job receives some percentage of CPU time based on share of "tickets"
  - Each job receives an allotment of tickets
  - % of tickets corresponds to potential share of a resource
  - Can conceptually schedule any resource this way
    - CPU, disk I/O, memory

LOTTERY SCHEDULER

- Simple implementation
  - Just need a random number generator
    - Picks the winning ticket
  - Maintain a data structure of jobs and tickets (list)
  - Traverse list to find the owner of the ticket
  - Consider sorting the list for speed

LOTTERY SCHEDULER IMPLEMENTATION




```c
// counter: used to track if we've found the winner yet
int counter = 0;

// winner: use some call to a random number generator to
// get a value, between 0 and the total # of tickets
int winner = getrandom(0, totaltickets);

// current: use this to walk through the list of jobs
node_t *current = head;

// loop until the sum of ticket values is > the winner
while (current) {
        counter = counter + current->tickets;
        if (counter > winner)
                break; // found the winner
        current = current->next;
}
// 'current' is the winner: schedule it...
```

TICKET MECHANISMS

- Ticket currency / exchange
  - User allocates tickets in any desired way
  - OS converts user currency into global currency
- Example:
  - There are 200 global tickets assigned by the OS

User A → *500* (A's currency) to A1 → *50* (global currency)
→ *500* (A's currency) to A2 → *50* (global currency)

User B → *10* (B's currency) to B1 → *100* (global currency)

TICKET MECHANISMS - 2

- Ticket transfer
  - Temporarily hand off tickets to another process
- Ticket inflation
  - Process can temporarily raise or lower the number of tickets it owns
  - If a process needs more CPU time, it can boost tickets.

LOTTERY SCHEDULING

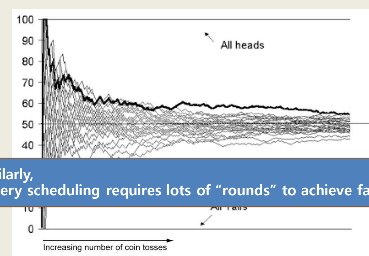
- Scheduler picks a <u>**winning**</u> ticket
  - Load the job with the winning ticket and run it
- Example:
  - Given 100 tickets in the pool
    - Job A has 75 tickets: 0 - 74
    - Job B has 25 tickets: 75 – 99

Scheduler's winning tickets:	63	85	70	39	76	17	29	41	36	39	10	99	68	83	63
Scheduled job:	A	B	A	A	B	A	A	A	A	A	A	B	A	B	A

- But what do we know about probability of a coin flip?

COIN FLIPPING

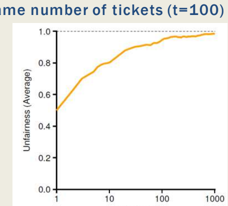
- Equality of distribution (fairness) requires a lot of flips!



Similarly,
Lottery scheduling requires lots of "rounds" to achieve fairness.

LOTTERY FAIRNESS

- With two jobs
  - Each with the same number of tickets (t=100)



When the job length is not very long, average unfairness can be <u>**quite severe**</u>.

LOTTERY SCHEDULING CHALLENGES

- What is the best approach to assign tickets to jobs?
  - Typical approach is to assume users know best
  - Users are provided with tickets, which they allocate as desired
- How should the OS automatically distribute tickets upon job arrival?
  - What do we know about incoming jobs a priori ?
  - Ticket assignment is really an open problem…

STRIDE SCHEDULER

- Addresses statistical probability issues with lottery scheduling
- Instead of guessing a random number to select a job, simply count…

STRIDE SCHEDULER - 2

- Jobs have a “stride” value
  - A stride value describes the counter pace when the job should give up the CPU
  - Stride value is **inverse in proportion** to the job’s number of tickets (more tickets = smaller stride)
- Total system tickets = 10,000
  - Job A has 100 tickets → A_{stride} = 10000/100 = 100 stride
  - Job B has 50 tickets → B_{stride} = 10000/50 = 200 stride
  - Job C has 250 tickets → C_{stride} = 10000/250 = 40 stride
- Stride scheduler tracks “pass” values for each job (A, B, C)

STRIDE SCHEDULER - 3

- Basic algorithm:
  1. Stride scheduler picks job with the lowest pass value
  2. Scheduler increments job’s pass value by its stride and starts running
  3. Stride scheduler increments a counter
  4. When counter exceeds pass value of current job, pick a new job (go to 1)
- KEY: When the counter reaches a job’s “PASS” value, the scheduler passes on to the next job…

STRIDE SCHEDULER - EXAMPLE

- Stride values
  - Tickets = priority to select job
  - Stride is inverse to tickets
  - Lower stride = more chances to run (higher priority)

Priority
C stride = 40
A stride = 100
B stride = 200

STRIDE SCHEDULER EXAMPLE - 2

- Three-way tie: randomly pick job A (all pass values=0)
- Set A’s pass value to A’s stride = 100
- Increment counter until > 100
- Pick a new job: two-way tie

Tickets
C = 250
A = 100
B = 50

Pass(A) (stride=100)	Pass(B) (stride=200)	Pass(C) (stride=40)	Who Runs?
0	0	0	A
100	0	0	B
100	200	0	C
100	200	40	C
100	200	80	C
100	200	120	A
200	200	120	C
200	200	160	C
200	200	200	…

Initial job selection is random. All @ 0

C has the most tickets and receives a lot of opportunities to run…

STRIDE SCHEDULER EXAMPLE - 3

- We set A’s counter (pass value) to A’s stride = 100
- Next scheduling decision between B (pass=0) and C (pass=0)
  - Randomly choose B
- C has the lowest counter for next 3 rounds

Tickets
C = 250
A = 100
B = 50

Pass(A) (stride=100)	Pass(B) (stride=200)	Pass(C) (stride=40)	Who Runs?
0	0	0	A
100	0	0	B
100	200	0	C
100	200	40	C
100	200	80	C
100	200	120	A
200	200	120	C
200	200	160	C
200	200	200	…

C has the most tickets and is selected to run more often …

STRIDE SCHEDULER EXAMPLE - 4

- Job counters support determining which job to run next
- Over time jobs are scheduled to run based on their priority represented as their **share of tickets…**
- **Tickets are analogous to job priority**

Tickets
C = 250
A = 100
B = 50

Pass(A) (stride=100)	Pass(B) (stride=200)	Pass(C) (stride=40)	Who Runs?
0	0	0	A
100	0	0	B
100	200	0	C
100	200	40	C
100	200	80	C
100	200	120	A
200	200	120	C
200	200	160	C
200	200	200	…

LINUX: COMPLETELY FAIR SCHEDULER (CFS)

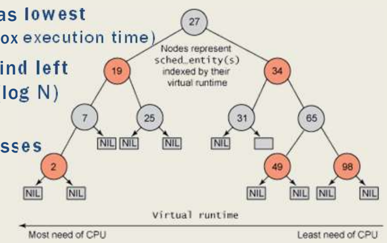
- Linux ≥ 2.6.23: Completely Fair Scheduler (CFS)
- Linux < 2.6.23: O(1) scheduler
- Every thread/process has a scheduling class (policy):
- **Normal classes**: SCHED_OTHER (TS), SCHED_IDLE, SCHED_BATCH
  - TS = Time Sharing
- **Real-time classes**: SCHED_FIFO (FF), SCHED_RR (RR)
- Show scheduling class and priority:
- `ps -elfc`
- `ps ax -o pid,ni,cls,pri,cmd`

COMPLETELY FAIR SCHEDULER - 2

- Loosely based on the stride scheduler
- CFS models system as a Perfect Multi-Tasking System
  - In perfect system every process of the same priority (class) receive exactly $1/n^{th}$ of the CPU time
- Scheduling classes each have a runqueue
  - Groups process of same priority
  - Process priority groups use different sets of runqueues for priorities
  - Scheduler picks task with lowest accumulative runtime to run
  - Time quantum varies based on how many jobs in shared runqueue
    - Time quantum is proportional to system CPU load in the runqueue
    - No fixed time quantum (e.g. 10 ms)

COMPLETELY FAIR SCHEDULER – 3

- Runqueues are stored using a linux red-black tree
  - Self balancing binary tree - nodes indexed by `vruntime`
- Leftmost node has lowest `vruntime` (approx execution time)
- Walking tree to find left most node is ~O(log N) for N nodes
- Completed processes removed



COMPLETELY FAIR SCHEDULER - 4

- CFS tracks virtual run time in vruntime variable
- The task on a given runqueue with the lowest `vruntime` is scheduled next
- `struct sched_entity` contains `vruntime` parameter
  - Describes process execution time in nanoseconds
  - Value is not pure runtime, but weighted based on priority
  - Perfect scheduler → achieve equal `vruntime` for all processes of same priority
- Key takeaway: ***identifying the next job to schedule is really fast!***

CFS: JOB PRIORITY

- Time slice: Linux ***"Nice value"***
  - Nice value predates the CFS scheduler
  - Top shows nice values
  - Process command (nice & priority): `ps ax -o pid,ni,cmd,%cpu, pri`
- Nice Values: from -20 to 19
  - Lower is ***higher*** priority, default is 0
  - Vruntime is a weighted time measurement
  - Priority weights the calculation of vruntime within a runqueue to give high priority jobs a boost.
    - Influences job's position in rb-tree

CFS: TIME QUANTUM

- Scheduling quantum is calculated at runtime based on targeted latency and total number of running processes
- Will vary between:
- `cat /proc/sys/kernel/sched_min_granularity_ns` (3 ms – minimum quantum)
- `cat /proc/sys/kernel/sched_latency_ns` (24 ms – target quantum)
- Target quantum (latency):
  - Interval during which task should run at least once
  - Automatically increases as number of jobs increase

CFS: TIME QUANTUM - 2

- How do we map a nice value to an actual CPU time quantum (timeslice) (ms)? What is the best mapping?
- O(1) scheduler (< 2.6.23)
  - tried to map nice value to timeslice (fixed allotment)
- Linux completely fair scheduler
  - Nice value suggests priority to assign runqueue for job
  - Time proportion varies based on # of jobs in runqueue
  - With fewer jobs in runqueue, time proportion is larger

COMPLETELY FAIR SCHEDULER - 5

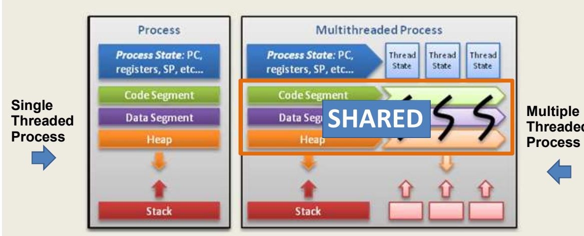
- More information:
- Man page: “man sched” : Describes Linux scheduling API
- http://manpages.ubuntu.com/manpages/bionic/man7/sched.7.html
- https://www.kernel.org/doc/Documentation/scheduler/sched-design-CFS.txt
- https://en.wikipedia.org/wiki/Completely_Fair_Scheduler
- See paper: The Linux Scheduler – a Decade of Wasted Cores
- http://www.ece.ubc.ca/~sasha/papers/eurosys16-final29.pdf

CHAPTER 26 - CONCURRENCY: AN INTRODUCTION

OBJECTIVES

- Introduction to threads
- Race condition
- Critical section
- Thread API

THREADS



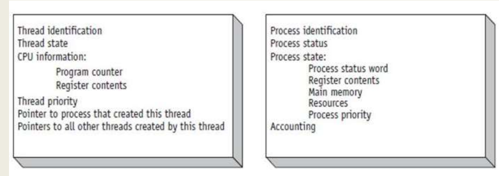
©Alfred Park, http://randu.org/tutorials/threads

THREADS - 2

- Enables a single process (program) to have multiple "workers"
  - This is parallel programming…
- Supports independent path(s) of execution within a program *with shared memory …*
- Each thread has its own Thread Control Block (TCB)
  - PC, registers, SP, and stack
- Threads share code segment, memory, and heap are shared
- ***What is an embarrassingly parallel program?***

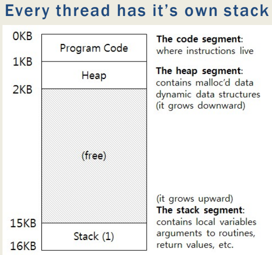
PROCESS AND THREAD METADATA

- Thread Control Block vs. Process Control Block

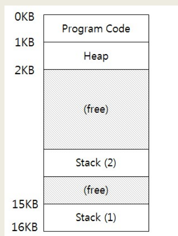


SHARED ADDRESS SPACE

- Every thread has it's own stack / PC



A Single-Threaded Address Space



Two threaded Address Space

THREAD CREATION EXAMPLE

```c
#include <stdio.h>
#include <assert.h>
#include <pthread.h>

void *mythread(void *arg) {
    printf("%s\n", (char *) arg);
    return NULL;
}

int
main(int argc, char *argv[]) {
    pthread_t p1, p2;
    int rc;
    printf("main: begin\n");
    rc = pthread_create(&p1, NULL, mythread, "A"); assert(rc == 0);
    rc = pthread_create(&p2, NULL, mythread, "B"); assert(rc == 0);
    // join waits for the threads to finish
    rc = pthread_join(p1, NULL); assert(rc == 0);
    rc = pthread_join(p2, NULL); assert(rc == 0);
    printf("main: end\n");
    return 0;
}
```


POSSIBLE ORDERINGS OF EVENTS

int main()	Thread 1	Thread 2
Starts running		
Prints 'main: begin'		
Creates Thread 1		
Creates Thread 2		
Waits for T1		
	Runs	
	Prints 'A'	
	Returns	
Waits for T2		
		Runs
		Prints 'B'
		Returns
Prints 'main: end'		

POSSIBLE ORDERINGS OF EVENTS - 2

int main()	Thread 1	Thread 2
Starts running		
Prints 'main: begin'		
Creates Thread 1		
	Runs	
	Prints 'A'	
	Returns	
Creates Thread 2		
		Runs
		Prints 'B'
		Returns
Waits for T1	*Returns immediately*	
Waits for T2		*Returns immediately*
Prints 'main: end'		

POSSIBLE ORDERINGS OF EVENTS - 3

int main()	Thread 1	Thread 2
Starts running		
Prints 'main: begin'		
Creates Thread 1		
Creates Thread 2		
Waits for T1		
	Runs	
	Prints 'A'	
	Returns	
Waits for T2		*Immediately returns*
Prints 'main: end'		

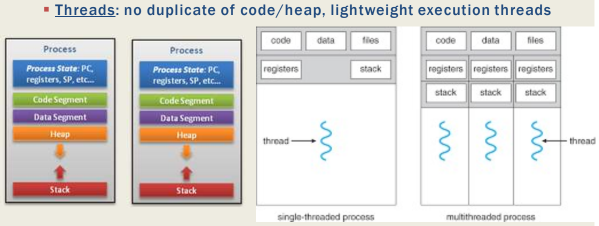
What if execution order of events in the program matters?

COUNTER EXAMPLE

- Counter example
- A + B : ordering
- Counter: incrementing global variable by two threads
- ***Is the counter example embarrassingly parallel?***
- ***What does the parallel counter program require?***

PROCESSES VS. THREADS

- What's the difference between forks and threads?
  - Forks: duplicate a process
  - Think of ***CLONING*** **-** There will be two identical processes at the end
  - Threads: no duplicate of code/heap, lightweight execution threads



RACE CONDITION

- What is happening with our counter?
  - When counter=50, consider code: counter = counter + 1
  - If synchronized, counter will = 52

```
                                                         (after instruction)
OS              Thread1              Thread2               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    51
```


CRITICAL SECTION

- Code that accesses a shared variable must not be ***concurrently*** executed by more than one thread
- Multiple *active* threads inside a ***critical section*** produce a ***race condition***.
- ***Atomic execution*** (*all code executed as a unit*) must be ensured in ***critical*** sections
  - These sections must be ***mutually exclusive***

LOCKS

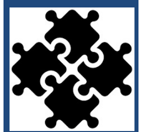
- To demonstrate how critical section(s) can be executed "atomically-*as a unit*" Chapter 27 & beyond introduce locks

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

Critical section

- Counter example revisited

CHAPTER 27 - LINUX THREAD API



THREAD CREATION

- pthread_create

```
#include <pthread.h>

int
pthread_create(      pthread_t*          thread,
                 const pthread_attr_t*  attr,
                 void*                  (*start_routine)(void*),
                 void*                  arg);
```

- thread: thread struct
- attr: stack size, scheduling priority… (*optional*)
- start_routine: function pointer to thread routine
- arg: argument to pass to thread routine (*optional*)

PTHREAD_CREATE – PASS ANY DATA

```
#include <pthread.h>

typedef struct __myarg_t {
        int a;
        int b;
} myarg_t;

void *mythread(void *arg) {
        myarg_t *m = (myarg_t *) arg;
        printf("%d %d\n", m->a, m->b);
        return NULL;
}

int main(int argc, char *argv[]) {
        pthread_t p;
        int rc;

        myarg_t args;
        args.a = 10;
        args.b = 20;
        rc = pthread_create(&p, NULL, mythread, &args);
        …
}
```


PASSING A SINGLE VALUE

Using this approach on your Ubuntu VM, How large (in bytes) can the primitive data type be?

How large (in bytes) can the primitive data type be on a 32-bit operating system?

```
        int rc, m;
        pthread_create(&p, NULL, mythread, (void *) 100);
        pthread_join(p, (void **) &m);
        printf("returned %d\n", m);
        return 0;
}
```


WAITING FOR THREADS TO FINISH

```
int pthread_join(pthread_t thread, void **value_ptr);
```

- thread: which thread?
- value_ptr: pointer to return value type is dynamic / agnostic
- Returned values *must* be on the heap
- Thread stacks destroyed upon thread termination (join)
- Pointers to thread stack memory addresses are invalid
  - May appear as gibberish or lead to crash (seg fault)
- Not all threads join – ***What would be Examples ??***

What will this code do?

```
struct myarg {
  int a;
  int b;
};

void *worker(void *arg)
{
  struct myarg *input = (struct myarg *) arg;
  printf("a=%d b=%d\n",input->a, input->b);
  struct myarg output;
  output.a = 1;
  output.b = 2;
  return (void *) &output;
}

int main (int argc, char * argv[])
{
  pthread_t p1;
  struct myarg args;
  struct myarg *ret_args;
  args.a = 10;
  args.b = 20;
  pthread_
  pthread_
  printf("
  return 0;
}
```

Data on thread stack

```
$ ./pthread_struct
a=10 b=20
Segmentation fault (core dumped)
```

How can this code be fixed?

How about this code?

```
struct myarg {
  int a;
  int b;
};

void *worker(void *arg)
{
  struct myarg *input = (struct myarg *) arg;
  printf("a=%d b=%d\n",input->a, input->b);
  input->a = 1;
  input->b = 2;
  return (void *) &input;
}

int main (int argc, char * argv[])
{
  pthread_t p1;
  struct myarg args;
  struct myarg *ret_args;
  args.a = 10;
  args.b = 20;
  pthread_create(&p1, NULL, worker, &args);
  pthread_join(p1, (void *)&ret_args);
  printf("returned %d %d\n", ret_args->a, ret_args->b);
  return 0;
}
```

```
$ ./pthread_struct
a=10 b=20
returned 1 2
```


ADDING CASTS

- Casting
- Suppresses compiler warnings when passing "typed" data where (void) or (void *) is called for
- Example: uncasted capture in pthread_join

```
pthread_int.c: In function 'main':
pthread_int.c:34:20: warning: passing argument 2 of 'pthread_join'
from incompatible pointer type [-Wincompatible-pointer-types]
   pthread_join(p1, &p1val);
```

- Example: uncasted return

```
In file included from pthread_int.c:3:0:
/usr/include/pthread.h:250:12: note: expected 'void **' but argument
is of type 'int **'
 extern int pthread_join (pthread_t __th, void **__thread_return);
```


ADDING CASTS - 2

- pthread_join

```
int * p1val;
int * p2val;
pthread_join(p1, (void *)&p1val);
pthread_join(p2, (void *)&p2val);
```

- return from thread function

```
int * counterval = malloc(sizeof(int));
*counterval = counter;
return (void *) counterval;
```


LOCKS

- pthread_mutex_t data type
- /usr/include/bits/pthread_types.h

```
// Global Address Space
static volatile int counter = 0;
pthread_mutex_t lock;

void *worker(void *arg)
{
  int i;
  for (i=0;i<10000000;i++)  {
    int rc = pthread_mutex_lock(&lock);
    assert(rc==0);
    counter = counter + 1;
    pthread_mutex_unlock(&lock);
  }
  return NULL;
}
```


LOCKS - 2

- Ensure critical sections are executed atomically-*as a unit*
  - Provides implementation of "***Mutual Exclusion***"
- API

```
int pthread_mutex_lock(pthread_mutex_t *mutex);
int pthread_mutex_unlock(pthread_mutex_t *mutex);
```

- Example w/o initialization & error checking

```
pthread_mutex_t lock;
pthread_mutex_lock(&lock);
x = x + 1; // or whatever your critical section is
pthread_mutex_unlock(&lock);
```

  - Blocks forever until lock can be obtained
  - Enters critical section once lock is obtained
  - Releases lock

LOCK INITIALIZATION

- Assigning the constant

```
pthread_mutex_t lock = PTHREAD_MUTEX_INITIALIZER;
```

- API call:

```
int rc = pthread_mutex_init(&lock, NULL);
assert(rc == 0); // always check success!
```

- Initializes mutex with attributes specified by 2nd argument
- If NULL, then default attributes are used
- Upon initialization, the mutex is initialized and unlocked

LOCKS - 3

- Error checking wrapper

```
// Use this to keep your code clean but check for failures
// Only use if exiting program is OK upon failure
void Pthread_mutex_lock(pthread_mutex_t *mutex) {
    int rc = pthread_mutex_lock(mutex);
    assert(rc == 0);
}
```

- What if lock can't be obtained?

```
int pthread_mutex_trylock(pthread_mutex_t *mutex);
int pthread_mutex_timelock(pthread_mutex_t *mutex,
                           struct timespec *abs_timeout);
```

- trylock – returns immediately (fails) if lock is unavailable
- timelock – tries to obtain a lock for a specified duration

CONDITIONS AND SIGNALS

- Condition variables support "signaling" between threads

```
int pthread_cond_wait(pthread_cond_t *cond,
                      pthread_mutex_t *mutex);
int pthread_cond_signal(pthread_cond_t *cond);
```

- pthread_cont_t datatype
- pthread_cond_wait()
  - Puts thread to "sleep" (waits) (THREAD is BLOCKED)
  - Threads added to FIFO queue, lock is released
  - Waits ***(listens)*** for a "signal" (NON-BUSY WAITING, no polling)
  - When signal occurs, interrupt fires, wakes up first thread, (THREAD is RUNNING), lock is provided to thread

CONDITIONS AND SIGNALS - 2

```
int pthread_cond_signal(pthread_cond_t * cond);
int pthread_cond_broadcast(pthread_cond_t * cond);
```

- pthread_cond_signal()
  - Called to send a "signal" to wake-up first thread in FIFO "wait" queue
  - The goal is to unblock a thread to respond to the signal
- pthread_cond_broadcast()
  - Unblocks ***all*** threads in FIFO "wait" queue, currently blocked on the specified condition variable
  - Broadcast is used when all threads should wake-up for the signal
- Which thread is unblocked first?
  - Determined by OS scheduler (based on priority)
  - Thread(s) awoken based on placement order in FIFO wait queue
  - When awoken threads acquire lock as in pthread_mutex_lock()

CONDITIONS AND SIGNALS - 3

- Wait example:

```
pthread_mutex_t lock = PTHREAD_MUTEX_INITIALIZER;
pthread_cond_t cond = PTHREAD_COND_INITIALIZER;

pthread_mutex_lock(&lock);
while (initialized == 0)
    pthread_cond_wait(&cond, &lock);
// Perform work that requires lock
a = a + b;
pthread_mutex_unlock(&lock);
```

- wait puts thread to sleep, releases lock
- when awoken, lock reacquired (but then released by this code)
- When initialized, another thread signals

```
pthread_mutex_lock(&lock);
initialized = 1;
pthread_cond_signal(&init);
pthread_mutex_unlock(&lock);
```

State variable set, Enables other thread(s) to proceed above.

CONDITION AND SIGNALS - 4

```
pthread_mutex_t lock = PTHREAD_MUTEX_INITIALIZER;
pthread_cond_t cond = PTHREAD_COND_INITIALIZER;

pthread_mutex_lock(&lock);
while (initialized == 0)
    pthread_cond_wait(&cond, &lock);
// Perform work that requires lock
a = a + b;
pthread_mutex_unlock(&lock);
```

- Why do we wait inside a while loop?
- The while ensures upon awakening the condition is rechecked
  - A signal is raised, but the pre-conditions required to proceed may have not been met. **MUST CHECK STATE VARIABLE**
  - Without checking the state variable the thread may proceed to execute when it should not. (e.g. too early)

PTHREADS LIBRARY

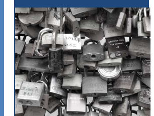
- Compilation
  - gcc –pthread pthread.c –o pthread
  - Requires explicitly linking the library with compiler flag
  - Use makefile to provide compiler arguments
- List of pthread manpages
  - man –k pthread

SAMPLE MAKEFILE

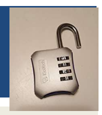
```
CC=gcc
CFLAGS=-pthread -I. -Wall

binaries=pthread pthread_int pthread_lock_cond pthread_struct

all: $(binaries)

pthread_mult: pthread.c pthread_int.c
    $(CC) $(CFLAGS) $^ -o $@

clean:
    $(RM) -f $(binaries) *.o
```

- Example builds multiple single file programs
  - All target
- pthread_mult
  - Example if multiple source files should produce a single executable
- clean target

CHAPTER 28 – LOCKS



LOCKS



- Ensure critical section(s) are executed atomically-*as a unit*
  - Only one thread is allowed to execute a critical section at any given time
  - Ensures the code snippets are "mutually exclusive"
- Protect a global counter:

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

- A "critical section":

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


LOCKS - 2

- Lock variables are called "MUTEX"
  - Short for mutual exclusion (that's what they guarantee)
- Lock variables store the state of the lock
- States
  - **Locked** (acquired or held)
  - **Unlocked** (available or free)
- Only 1 thread can hold a lock

LOCKS - 3

- `pthread_mutex_lock(&lock)`
  - Try to acquire lock
  - If lock is free, calling thread will acquire the lock
  - Thread with lock enters critical section
    - Thread "owns" the lock
- No other thread can acquire the lock before the owner releases it.

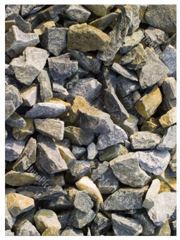
LOCKS - 4

- Program can have many mutex (lock) variables to "serialize" many critical sections
- Locks are also used to protect data structures
  - Prevent multiple threads from changing the same data simultaneously
  - Programmer can make sections of code "granular"
    - Fine grained – means just one grain of sand at a time through an hour glass
  - Similar to relational database transactions
    - DB transactions prevent multiple users from modifying a table, row, field

FINE GRAINED?

- Is this code a good example of *"fine grained parallelism"*?

```
pthread_mutex_lock(&lock);
a = b++;
b = a * c;
*d = a + b +c;
FILE * fp = fopen ("file.txt", "r");
fscanf(fp, "%s %s %s %d", str1, str2, str3, &e);
ListNode *node = mylist->head;
Int i=0
while (node) {
  node->title = str1;
  node->subheading = str2;
  node->desc = str3;
  node->end = *e;
  node = node->next;
  i++
}
e = e - i;
pthread_mutex_unlock(&lock);
```



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FINE GRAINED PARALLELISM

```
pthread_mutex_lock(&lock_a);
pthread_mutex_lock(&lock_b);
a = b++;
pthread_mutex_unlock(&lock_b);
pthread_mutex_unlock(&lock_a);

pthread_mutex_lock(&lock_b);
b = a * c;
pthread_mutex_unlock(&lock_b);

pthread_mutex_lock(&lock_d);
*d = a + b +c;
pthread_mutex_unlock(&lock_d);

FILE * fp = fopen ("file.txt", "r");
pthread_mutex_lock(&lock_e);
fscanf(fp, "%s %s %s %d", str1, str2, str3, &e);
pthread_mutex_unlock(&lock_e);

ListNode *node = mylist->head;
int i=0 . . .
```

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EVALUATING LOCK IMPLEMENTATIONS

- Correctness
  - Does the lock work?
  - Are critical sections mutually exclusive? (atomic-*as a unit*?)
- Fairness
  - Are threads competing for a lock have a fair chance of acquiring it?
- Overhead

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BUILDING LOCKS

- Locks require hardware support
  - To minimize overhead, ensure fairness and correctness
  - Special "atomic-*as a unit*" instructions to support lock implementation
  - Atomic-*as a unit* exchange instruction
    - `XCHG`
  - Compare and exchange instruction
    - `CMPXCHG`
    - `CMPXCHG8B`
    - `CMPXCHG16B`

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HISTORICAL IMPLEMENTATION

- To implement mutual exclusion
  - Disable interrupts upon entering critical sections

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

- Any thread could disable system-wide interrupt
  - What if lock is never released?
- On a multiprocessor processor each CPU has its own interrupts
  - Do we disable interrupts for all cores simultaneously?
- While interrupts are disabled, they could be lost
  - If not queued…

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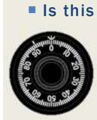
SPIN LOCK IMPLEMENTATION

- Operate without atomic-*as a unit* assembly instructions
- "Do-it-yourself" Locks
- Is this lock implementation: Correct? Fair? Performant?



```
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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DIY: CORRECT?

- Correctness requires luck… (e.g. *DIY lock is incorrect*)

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

- Here both threads have "acquired" the lock simultaneously

DIY: PERFORMANT?

```
void lock(lock_t *mutex)
{
  while (mutex->flag == 1);   // while lock is unavailable, wait…
  mutex->flag = 1;
}
```

- What is wrong with while(<cond>); ?
- Spin-waiting wastes time actively waiting for another thread
- while (1); will "peg" a CPU core at 100%
  - Continuously loops, and evaluates mutex->flag value…
  - Generates heat…

TEST-AND-SET INSTRUCTION

- C implementation: not atomic
  - Adds a simple check to basic spin lock
  - One a single core CPU system with preemptive scheduler:
  - Try this…

```
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
}
```

- lock() method checks that TestAndSet doesn't return 1
- Comparison is in the caller
- Single core systems are becoming scarce
- Try on a one-core VM

DIY: TEST-AND-SET - 2

- Requires a preemptive scheduler on single CPU core system
- Lock is never released without a context switch
- 1-core VM: occasionally will deadlock, doesn't miscount

```
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;
}
```


SPIN LOCK EVALUATION

- **Correctness:**
  - Spin locks guarantee: critical sections won't be executed simultaneously by (2) threads
- **Fairness:**
  - No fairness guarantee. Once a thread has a lock, nothing forces it to relinquish it…
- **Performance:**
  - Spin locks perform "busy waiting"
  - Spin locks are best for short periods of waiting
  - Performance is slow when multiple threads share a CPU
    - Especially for long periods

COMPARE AND SWAP

- Checks that the lock variable has the expected value FIRST, before changing its value
  - If so, make assignment
  - Return value at location
- Adds a comparison to TestAndSet
- Useful for wait-free synchronization
  - Supports implementation of shared data structures which can be updated atomically (*as a unit*) using the HW support CompareAndSwap instruction
  - Shared data structure updates become "wait-free"
  - Upcoming in Chapter 32

COMPARE AND SWAP

- Compare and Swap

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

- Spin loc

```
        ; // spin
}
```

1-core VM:
Count is correct, no deadlock

- X86 provides "**cmpxchgl**" compare-and-exchange instruction
  - **cmpxchg8b**
  - **cmpxchg16b**

TWO MORE "LOCK BUILDING" CPU INSTRUCTIONS

- Cooperative instructions used together to support synchronization on RISC systems
- No support on x86 processors
  - Supported by RISC: Alpha, PowerPC, ARM
- Load-linked (LL)
  - Loads value into register
  - Same as typical load
  - Used as a mechanism to track competition
- Store-conditional (SC)
  - Performs "mutually exclusive" store
  - Allows only one thread to store value

LL/SC LOCK

```
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
    }
}
```

- LL instruction loads pointer value (ptr)
- SC only stores if the load link pointer has not changed
- Requires HW support
  - C code is psuedo code

LL/SC LOCK - 2

```
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;
}
```

- Two instruction lock

QUESTIONS

COMPUTER BOOT SEQUENCE: OS WITH DIRECT EXECUTION

- What if programs could directly control the CPU / system?

OS	Program
1. Create entry for process list 2. Allocate memory for program 3. Load program into memory 4. Set up stack with `argc` / `argv` 5. Clear registers 6. Execute call `main()`	7. Run `main()` 8. Execute `return` from `main()`
9. Free memory of process 10. Remove from process list	

COMPUTER BOOT SEQUENCE: OS WITH DIRECT EXECUTION

- What if programs could directly control the CPU / system?

OS	Program
1. Create entry for process list 2. Allocate memory for argv 5. Clear registers 6. Execute call main()	7. Run main() 8. Execute return from main()
9. Free memory of process 10. Remove from process list	

Without *limits* on running programs, the OS wouldn't be in control of anything and would "just be a library"

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DIRECT EXECUTION - 2

- **With direct execution:**

How does the OS stop a program from running, and switch to another to support **time sharing?**

How do programs share disks and perform I/O if they are given direct control? Do they know about each other?

With direct execution, how can dynamic memory structures such as linked lists grow over time?

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CONTROL TRADEOFF

- **Too little control:**
  - No security
  - No time sharing
- **Too much control:**
  - Too much OS overhead
  - Poor performance for compute & I/O
  - Complex APIs (system calls), difficult to use

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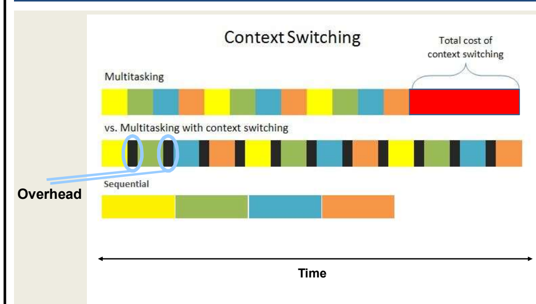
CONTEXT SWITCHING OVERHEAD



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