TCSS 422: OPERATING SYSTEMS

Proportional Share Schedulers, Introduction to Concurrency

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OFFICE HOURS – FALL 2021

- **Tuesdays:**
  - 4:00 to 4:30 pm - CP 229
  - 7:15 to 7:45+ pm – ONLINE via Zoom
- **Thursdays**
  - 4:15 to 4:45 pm – ONLINE via Zoom
  - 7:15 to 7:45+ pm – ONLINE via Zoom
- Or email for appointment
- Zoom link sent via Canvas Announcements

> Office Hours set based on Student Demographics survey feedback

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TEXT BOOK COUPON

- 15% off textbook code: **SPOOKY15** (*through Friday Oct 22*)
- https://www.lulu.com/shop/remzi-arpaci-dusseau-and-andrea-arpaci-dusseau/operating-systems-three-easy-pieces-softcover-version-100/paperback/product-23779877.html?page=1&pageSize=4

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OBJECTIVES – 10/21

- **Questions from 10/19**
- Assignment 0 - Due Fri Oct 22
- C Tutorial - Pointers, Strings, Exec in C - Due Fri Oct 29
- Quiz 1 and Quiz 2
- Chapter 9: Proportional Share Schedulers
  - Lottery scheduler
  - Ticket mechanisms
  - Stride scheduler
  - Linux Completely Fair Scheduler
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  - pthread_create/_join
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  - pthread_cond_wait/_signal/_broadcast

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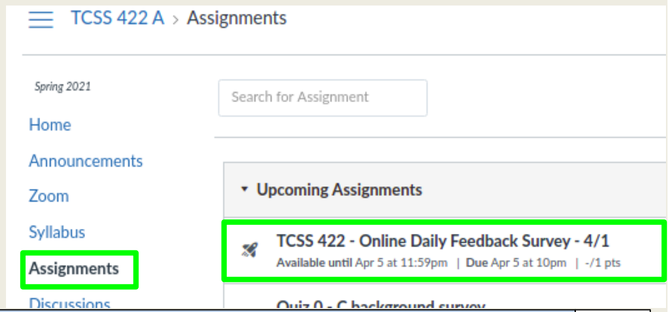
ONLINE DAILY FEEDBACK SURVEY

- Daily Feedback Quiz in Canvas – Available After Each Class
- Extra credit available for completing surveys ***ON TIME***
- Tuesday surveys: due by ~ Wed @ 11:59p
- Thursday surveys: due ~ Mon @ 11:59p



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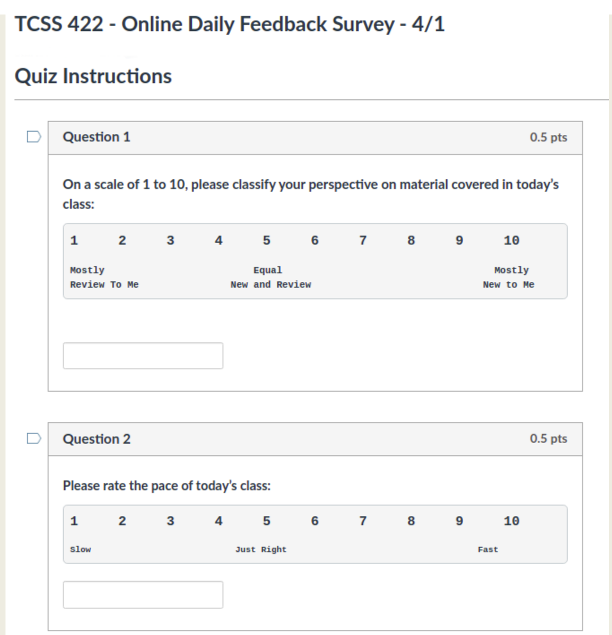

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MATERIAL / PACE

- Please classify your perspective on material covered in today's class (21 respondents):
- 1-mostly review, 5-equal new/review, 10-mostly new
- **Average – 6.48 (↓ - previous 6.62)**

- Please rate the pace of today's class:
- 1-slow, 5-just right, 10-fast
- **Average – 5.48 (↓ - previous 5.54)**

FEEDBACK

- ?

BONUS SESSION – EXAMPLE SCHEDULER PROBLEMS

- Bonus session on Zoom:
  Wed Oct 27 starting at 6:30pm
  - Approximately ~1 hour
- Will solve a series of example scheduling problems
  - Focus on: FIFO, SJF, STCF, RR, MLFQ
- Video will be recorded and posted
- **Midterm in class on Thursday November 4th**

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ASSIGNMENT 0 - DUE FRI OCT 22

- Due Friday Oct 22 @ 11:59pm
- Grace period: submission ok til Sun Oct 24 @ 11:59 AM
- Late submissions: ok til Tuesday Oct 26 @ 11:59pm

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QUIZ 1

- Active reading on Chapter 9 – Proportional Share Schedulers
- Posted in Canvas
- Due Tuesday November 2nd at 11:59pm
- Grace period til Thursday Nov 4th at 11:59 ** AM **
- Late submissions til Saturday Nov 6th at 11:59pm
- **Link:**
- **http://faculty.washington.edu/wlloyd/courses/tcss422/TCSS422_f2021_quiz_1.pdf**

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QUIZ 2

- Canvas Quiz – CPU Scheduling Problems

- Posted in Canvas
- Unlimited attempts permitted
- Due Thursday November 4th at 11:59pm
- Grace period til Saturday Nov 6th at 11:59 ** AM **
- Late submissions til Monday Nov 8th at 11:59pm

- Link:
- https://canvas.uw.edu/courses/1484473/quizzes/1555405

COMING SOON...

- Assignment #1
  - To be posted for next class, Tuesday Oct 26

- Midterm Exam
  - Thursday November 4th
  - In Class

CHAPTER 9 - PROPORTIONAL SHARE SCHEDULER

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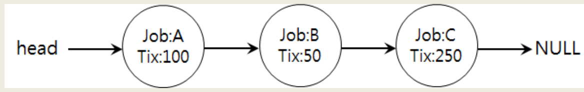
PROPORTIONAL SHARE SCHEDULER

- 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...
```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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

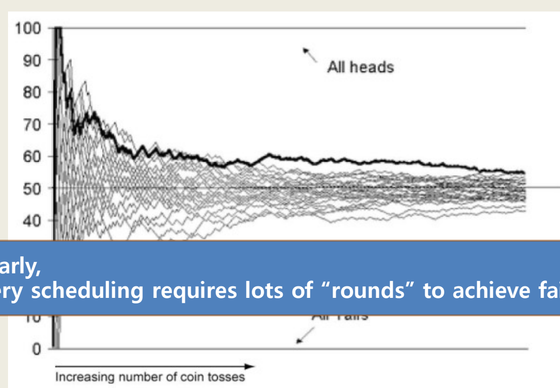
- Scheduler picks a **winning** ticket
  - Load the job with the winning ticket and run it
- Example:
  - Given 100 tickets in the pool
    - Job A has 75 tickets: 0 - 74
    - Job B has 25 tickets: 75 – 99

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

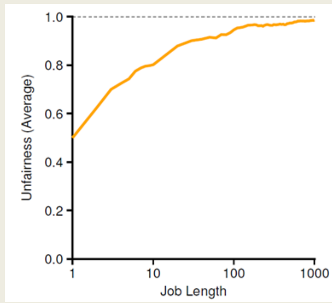
- Equality of distribution (fairness) requires a lot of flips!



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 **quite severe**.

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…

WE WILL RETURN AT 2:40PM

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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

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	...

Tickets
C = 250
A = 100
B = 50

Initial job selection is random. All @ 0

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

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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

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	...

Tickets
C = 250
A = 100
B = 50

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

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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	…

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LINUX: COMPLETELY FAIR SCHEDULER (CFS)

- Large Google datacenter study:
  "Profiling a Warehouse-scale Computer" (Kanev et al.)
- Monitored 20,000 servers over 3 years
- Found 20% of CPU time spent in the Linux kernel
- 5% of CPU time spent in the CPU scheduler!
- Study highlights importance for high performance OS kernels and CPU schedulers !

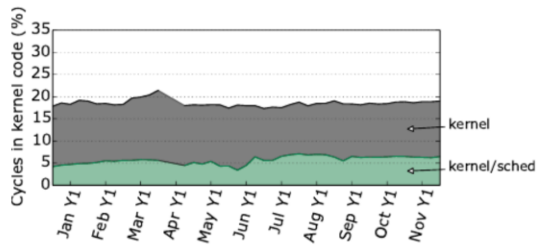


Figure 5: Kernel time, especially time spent in the scheduler, is a significant fraction of WSC cycles.

See: https://dl.acm.org/doi/pdf/10.1145/2749469.2750392

LINUX: COMPLETELY FAIR SCHEDULER (CFS)

- 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
- Each scheduling class has a runqueue
  - Groups process of same class
  - In class, scheduler picks task w/ lowest `vruntime` to run
  - Time slice varies based on how many jobs in shared runqueue
  - Minimum time slice prevents too many context switches (e.g. 3 ms)

COMPLETELY FAIR SCHEDULER - 2

- 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)

- How to show scheduling class and priority:
- `#class`
  `ps -elfc`
- `#priority (nice value)`
  `ps ax -o pid,ni,cls,pri,cmd`

COMPLETELY FAIR SCHEDULER - 3

- Linux ≥ 2.6.23: Completely Fair Scheduler (CFS)
- Linux < 2.6.23: O(1) scheduler

- Linux maintains simple counter (**vruntime**) to track how long each thread/process has run
- CFS picks process with lowest **vruntime** to run next

- CFS adjusts timeslice based on # of proc waiting for the CPU
- Kernel parameters that specify CFS behavior:

```
$ sudo sysctl kernel.sched_latency_ns
kernel.sched_latency_ns = 24000000
$ sudo sysctl kernel.sched_min_granularity_ns
kernel.sched_min_granularity_ns = 3000000
$ sudo sysctl kernel.sched_wakeup_granularity_ns
kernel.sched_wakeup_granularity_ns = 4000000
```

COMPLETELY FAIR SCHEDULER - 4

- Sched_min_granularity_ns (3ms)
  - Time slice for a process: busy system (w/ full runqueue)
  - If system has idle capacity, time slice exceed the min as long as difference in vruntime between running process and process with lowest vruntime is less than sched_wakeup_granularity_ns (4ms)
- Scheduling time period is: total cycle time for iterating through a set of processes where each is allowed to run (like round robin)
- Example:
  sched_latency_ns (24ms)
  if (proc in runqueue < sched_latency_ns/sched_min_granularity)
  or
  sched_min_granularity * number of processes in runqueue

Ref: https://www.systutorials.com/sched_min_granularity_ns-sched_latency_ns-cfs-affect-timeslice-processes/

CFS TRADEOFF

- **HIGH** sched_min_granularity_ns (timeslice)
  sched_latency_ns
  sched_wakeup_granularity_ns

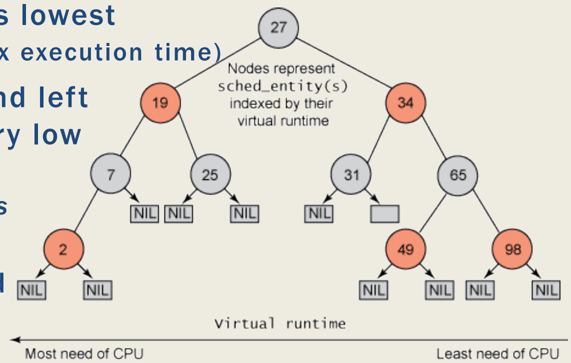
  reduced context switching → less overhead
  poor near-term fairness

- **LOW** sched_min_granularity_ns (timeslice)
  sched_latency_ns
  sched_wakreup_granularity_ns

  increased context switching → more overhead
  better near-term fairness

COMPLETELY FAIR SCHEDULER - 5

- 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 has very low big O complexity: *~O(log N) for N nodes*
- Completed processes removed



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CFS: JOB PRIORITY

- Time slice: Linux ***"Nice value"***
  - Nice predates the CFS scheduler
  - Top shows nice values
  - Process command (nice & priority):
    `ps ax -o pid,ni,cmd,%cpu, pri`

```
static const int prio_to_weight[40] = {
    /* -20 */ 88761, 71755, 56483, 46273, 36291,
    /* -15 */ 29154, 23254, 18705, 14949, 11916,
    /* -10 */  9548,  7620,  6100,  4904,  3906,
    /*  -5 */  3121,  2501,  1991,  1586,  1277,
    /*   0 */  1024,   820,   655,   526,   423,
    /*   5 */   335,   272,   215,   172,   137,
    /*  10 */   110,    87,    70,    56,    45,
    /*  15 */    36,    29,    23,    18,    15,
};
```

- 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

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COMPLETELY FAIR SCHEDULER - 6

- CFS tracks cumulative job 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, is weighted based on job priority
  - Perfect scheduler → achieve equal **`vruntime`** for all processes of same priority
- Sleeping jobs: upon return reset **`vruntime`** to lowest value in system
  - Jobs with frequent short sleep ***SUFFER !!***
- Key takeaway: ***identifying the next job to schedule is really fast!***

COMPLETELY FAIR SCHEDULER - 7

- 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

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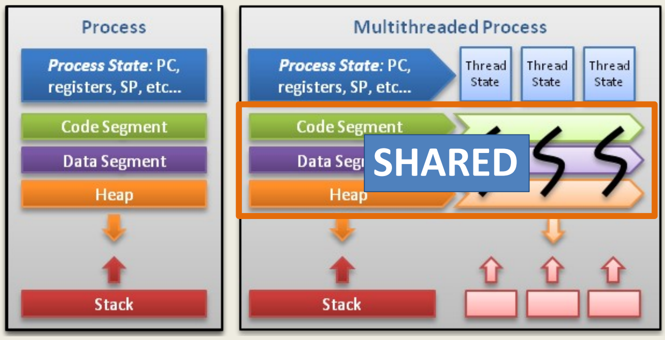
THREADS

Single Threaded Process



Multiple Threaded Process

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

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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?***

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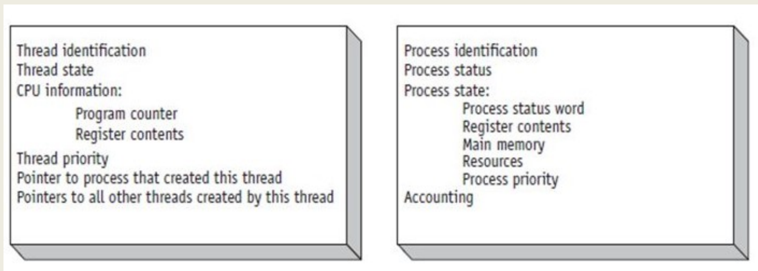
PROCESS AND THREAD METADATA

- Thread Control Block vs. Process Control Block



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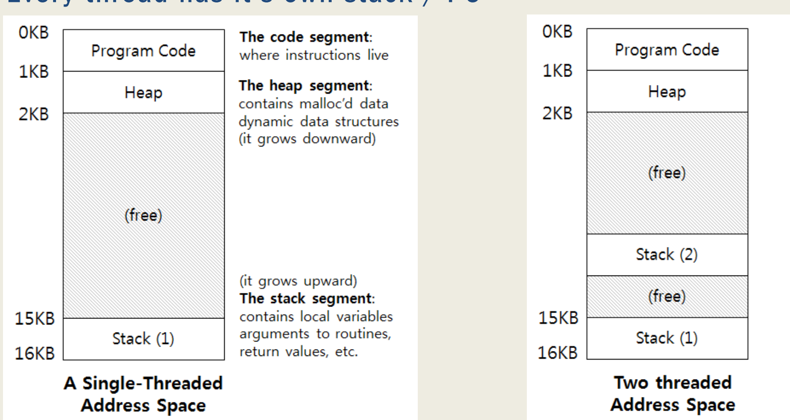
SHARED ADDRESS SPACE

- Every thread has it's own stack / PC



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THREAD CREATION EXAMPLE

```
#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'		

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POSSIBLE ORDERINGS OF EVENTS - 3

int main()	Thread 1	Thread 2
Starts running		
Prints 'main: begin'		
Creates Thread 1		
Creates Thread 2		
Waits for T		
	Runs	
	Prints 'A'	
	Returns	
Waits for T2		*Immediately returns*
Prints 'main: end'		

What if execution order of events in the program matters?

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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?***

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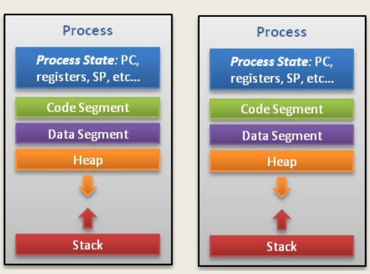
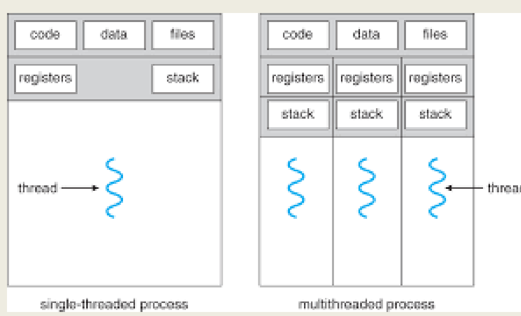
PROCESSES VS. THREADS

- 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 duplication of code/heap, lightweight execution threads





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OBJECTIVES – 10/21

- Questions from 10/19
- Assignment 0 - Due Fri Oct 22
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- Quiz 1 and Quiz 2
- Chapter 9: Proportional Share Schedulers
  - Lottery scheduler
  - Ticket mechanisms
  - Stride scheduler
  - Linux Completely Fair Scheduler
- Chapter 26: Concurrency: An Introduction
  - Introduction
  - **Race condition**
  - Critical section
- Chapter 27: Linux Thread API
  - pthread_create/_join
  - pthread_mutex_lock/_unlock/_trylock/_timelock
  - pthread_cond_wait/_signal/_broadcast

RACE CONDITION

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

OS	Thread1	Thread2	PC (after instruction)	%eax (after instruction)	counter (after instruction)
	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**

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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

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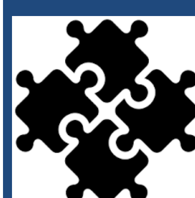
CHAPTER 27 - LINUX THREAD API



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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);
        …
}
```

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PASSING A SINGLE VALUE

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

```
        printf("%d\n", m);
```

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;
}
```

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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 ??***

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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?

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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;
```


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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

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  - **pthread_cond_wait/_signal/_broadcast**

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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

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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()`

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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.

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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 requires special option to require programs with pthreads:
  - gcc –pthread pthread.c –o pthread
  - Explicitly links library with compiler flag
  - RECOMMEND: using 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

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QUESTIONS

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