Threads

To do …

- Why threads?
- Thread model & implementation
- …
- Next time: Synchronization

What's in a process

- A process consists of (at least):
  - An address space
    - Code and data for the running program
  - Thread state
    - An execution stack and stack pointer (SP)
    - The program counter (PC)
    - Set of general-purpose processor registers and values
  - A set of OS resources
    - open files, network connections, …
- A lot of concepts bundled together!

Cooperating, concurrent tasks

- Many programs need to perform several, mostly independent tasks that do not need to be serialized
  - Web server – clients' requests, cart update, CC checks, …
  - Text editor – update screen, save file, spell check, …
  - Web client – multiple request for each piece of a site
  - Parallel program – large matrix multiplication in blocks
  - …

- Concurrency and parallelism
  - Concurrency – what's possible with infinite processors; for convenience
  - Parallelism – Your actual degree of parallel execution; for performance

How can we get this?

- Given the process abstraction as we know it
  - Fork several processes
  - Make each to map to the same address space to share data
    - See the shmget() system call for one way to do this (kind of)
- Not very efficient
  - Space: PCB, page tables, etc.
  - Time: Creating OS structures, fork and copy addr space, etc.
- Other equally bad alternatives for some of the cases
  - Entirely separate web servers
  - Finite-state machine or event-driven – a single process and asynchronous programming (non-blocking I/O)

What is actually needed

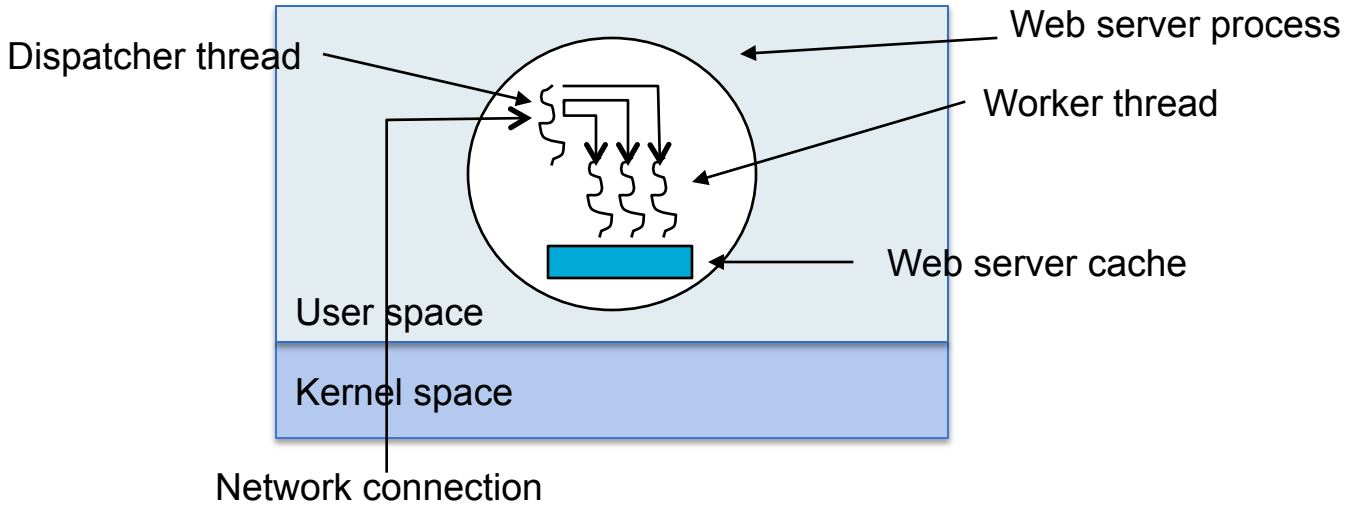
- In each examples
  - Everybody wants to run the same code
  - … wants to access the same data
  - … has the same privileges
  - … uses the same resources (open files, net connections, etc.)

- But … wants its own HW execution state
  - An execution stack & SP
  - PC indicating the next instruction
  - A set of general-purpose processor registers & their values

The thread model

- Traditionally
  - Process = resource grouping + execution stream

- Key idea with threads
  - Separate concept of a process (address space, etc.)
  - From the minimal “thread of control” (execution state)
  - Threads are concurrent executions sharing an address space (and some OS resources)



Threads and processes

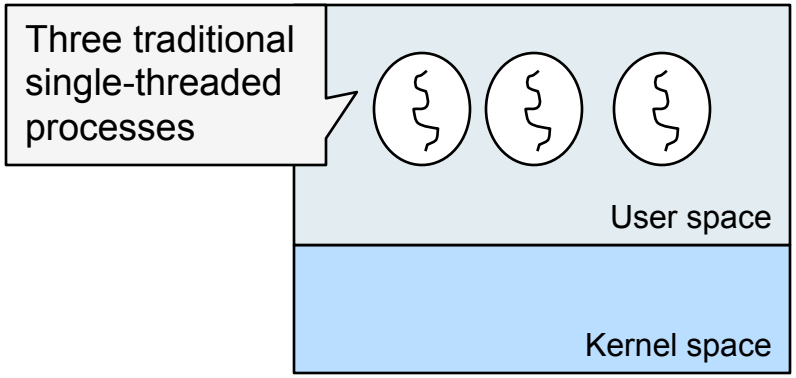
- Most modern OS's support both entities
  - Process – defines address space and gral process attributes
  - Thread – a sequential execution stream within a process

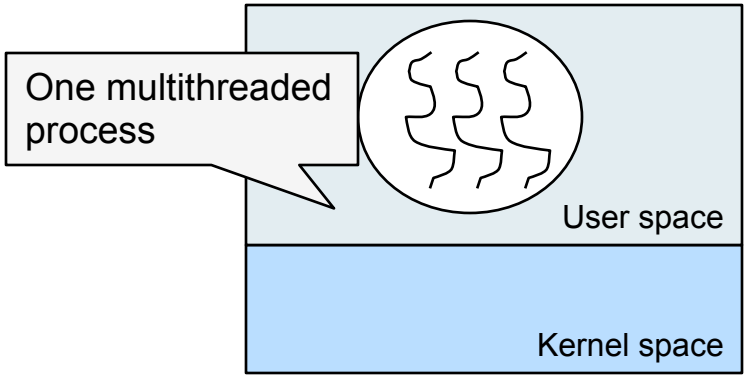
- A thread is bound to a process/address space
  - Address space provides isolation
    - If you can't name it, you can't use it (read or write)
  - So, communication between processes is difficult (you have to involve the OS), but sharing data between threads is cheap

- Threads become the unit of scheduling
  - Process / address spaces are just containers where threads execute

The classical thread model

- Threads and processes

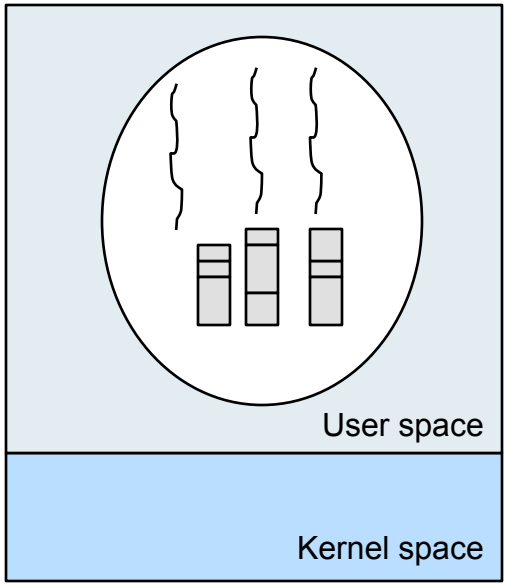




- Threads states ~ processes states
- Threads are not as independent as processes
  - All share same address space so they all can read, write or delete each other's stacks
  - There's no protection between threads (Should they be?)
  - Also share set of open files, child processes, signals, etc
    - If one thread opens a file, the file is visible to the others

The classical thread model

- Remember the per thread items
  - Program counter, registers, *stack*, state
  - Each thread's stack contains one frame for each procedure called but not yet returned from



- Typical thread calls

Thread call	**Description**
pthread_create	Create a new thread
pthread _exit	Terminate the calling thread
pthread_join	Wait for a specific thread to exit
pthread_yield	Release the CPU to let another thread run

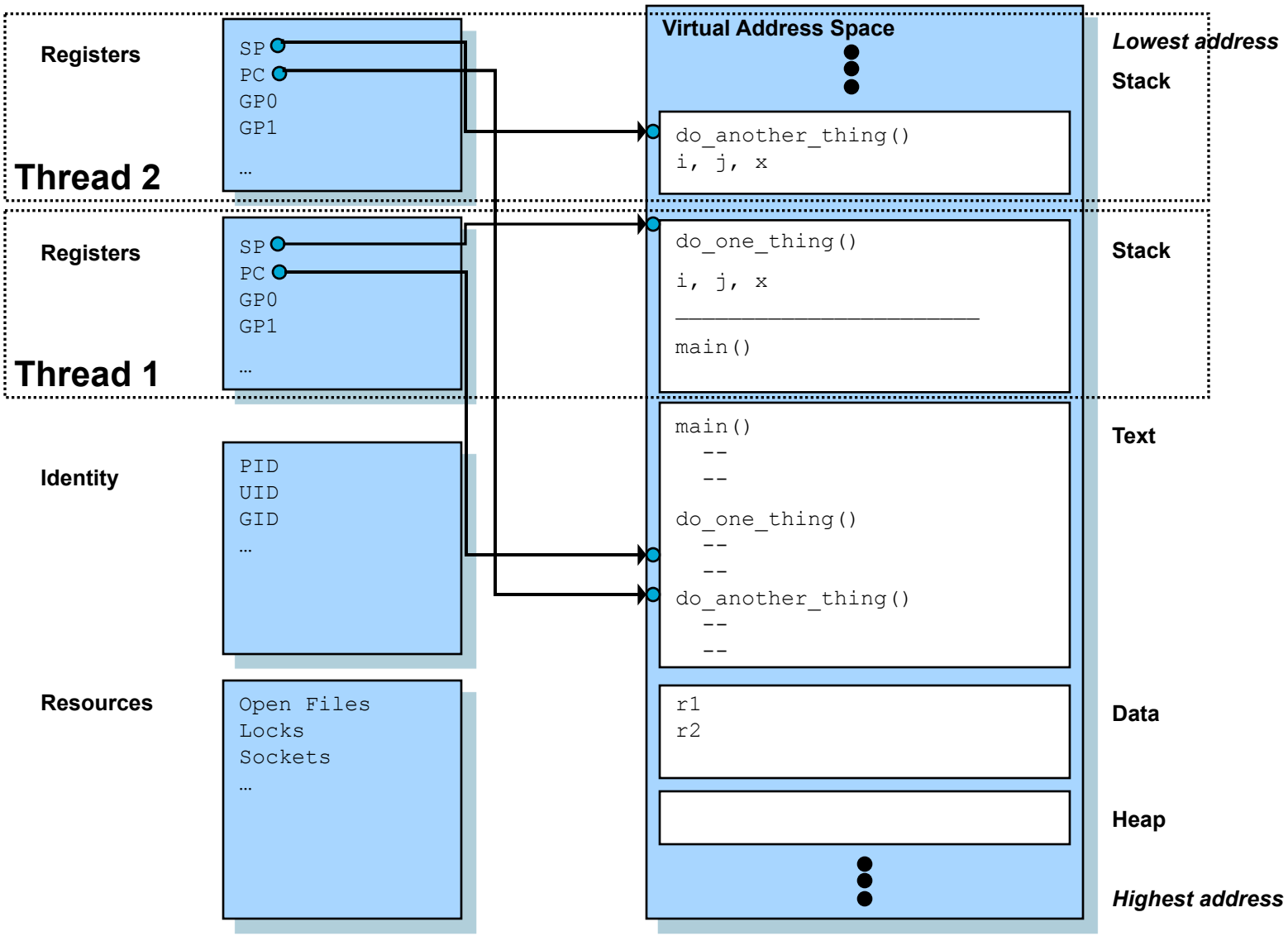
A simple example

```
int r1 = 0, r2 = 0;

void do_one_thing(int *ptimes)
{
  int i, j, x;

  for (i = 0; i < 4; i++) {
    printf("doing one\n");
    for (j = 0; j < 1000; j++)
      x = x + i;
    (*ptimes)++;
} /* do_one_thing! */

void do_another_thing(int *ptimes)
{
  int i, j, x;

  for (i = 0; i < 4; i++) {
    printf("doing another\n");
    for (j = 0; j < 1000; j++)
      x = x + i;
    (*ptimes)++;
} /* do_another_thing! */
```

```
void do_wrap_up(int one, int
   another)
{
  int total;
  total = one + another;
  printf("wrap up: one %d, another
    %d and total %d\n", one,
    another, total);
}
```

```
int main (int argc, char *argv[])
{
  do_one_thing(&r1);
  do_another_thing(&r2);
  do_wrap_up(r1,r2);
  return 0;
} /* main! */
```

Layout in memory & threading

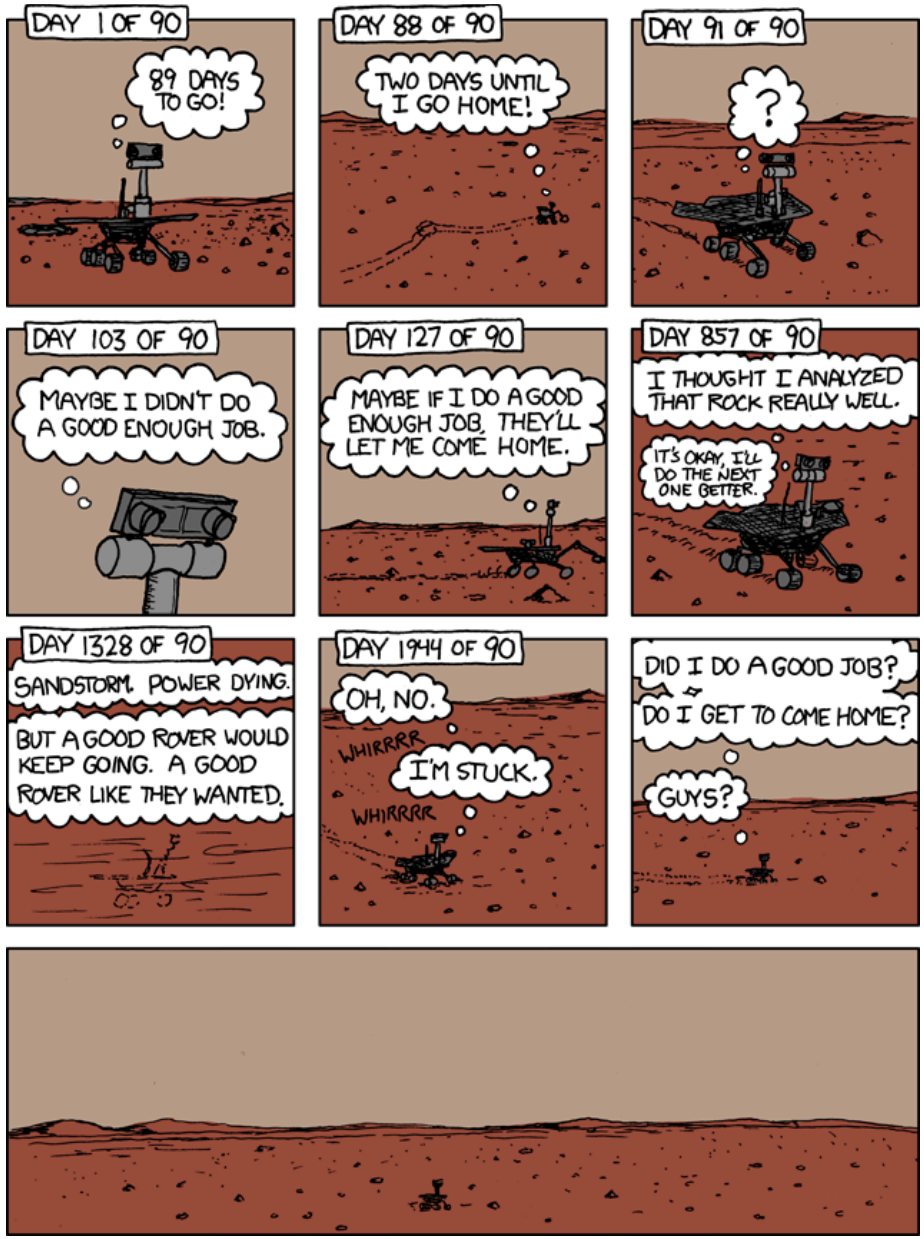


Benefits of threads

- Simpler programming model for concurrent activities
  - Multiple asynchronous events, handle with separate threads using a synchronous programming model
- Easier/faster to communicate between threads than processes
- Easier/cheaper to create/destroy than processes since they have no resources attached to them
- With good mix of CPU and I/O bound activities, better performance
- Even better if you have multiple CPUs

And now a short break …

Spirit
xkcd



Threads libraries

- Pthreads – POSIX standard (IEEE 1003.1c)
  - API specifies behavior of the thread library, implementation is up to the developers of the library
  - Common in UNIX OSs (Solaris, Linux, Mac OS X)

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

void pthread_exit(void *value_ptr);

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

int pthread_yield(void);

int pthread_attr_destroy(pthread_attr_t *attr);

int pthread_attr_init(pthread_attr_t *attr);
```

If you haven't seen one

```
#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("begin\n");
  rc = pthread_create(&p1, NULL, mythread, "A"); assert(rc == 0);
  rc = pthread_create(&p2, NULL, mythread, "B"); assert(rc == 0);

  rc = pthread_join(p1, NULL); assert(rc == 0);
  rc = pthread_join(p2, NULL); assert(rc == 0);
  printf("end\n");
  return 0;
}
```

Main	thread	thread
"begin"		
Create T1		
Create T2		
	"A"	
		"B"
Wait on T1		
Wait on T2		
"end"		

```
% gcc –o createThread createThread.c -pthread
```

Thread libraries

- …
- Win32 threads – slightly different (more complex API)
- Java threads
  - Managed by the JVM
  - May be created by
    - Extending Thread class
    - Implementing the Runnable interface
  - Implementation model depends on OS (one-to-one in Windows and Linux, but many-to-one in early Solaris)

Multithreaded C/POSIX

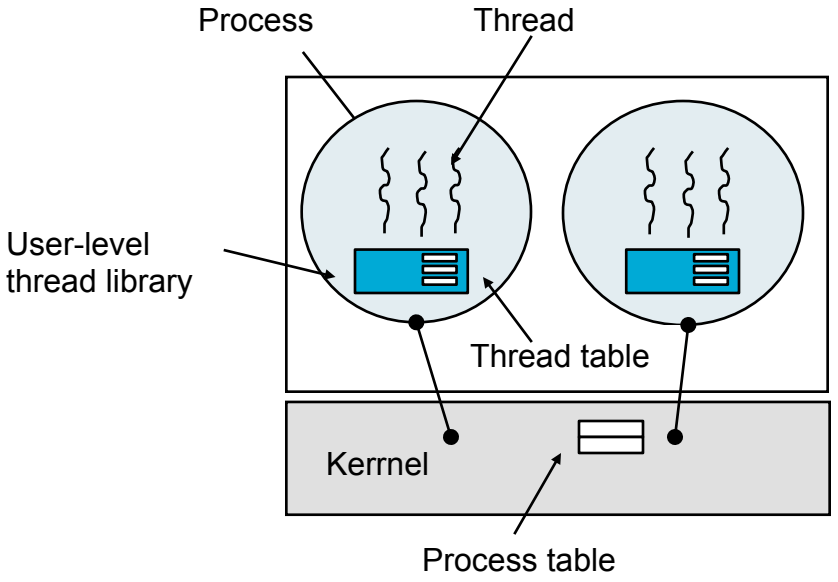
```
/* shared by thread(s) */
int sum;

/* runner: the thread */
void *runner(void *param)
{
  int i, upper = atoi(param);

  sum = 0;
  for (i = 1; i < upper; i++)
    sum += 1;
  pthread_exit(0);
} /* runner! */
```

$$sum = \sum_{i=0}^{N} i$$

```
int main (int argc, char *argv[])
{
  pthread_t tid;   /* thread id */

  /* set of thread attrs */
  pthread_attr_t attr;

  if (argc != 2 || atoi(argv[1]) < 0) {
    fprintf (stderr, "usage: %s <int>
   \n", argv[0]);
    exit(1);
  }

  /* get default attrs */
  pthread_attr_init(&attr);
  pthread_create(&tid, &attr, runner,
   argv[1]);

  /* wait to exit */
  pthread_join(tid, NULL);
  printf("sum = %d\n", sum);
  exit(0);
} /* main! */
```

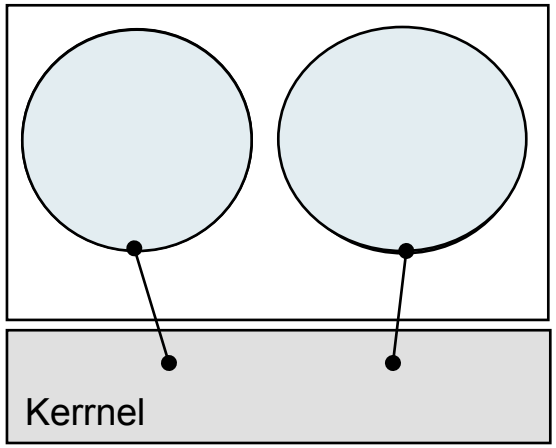
User-level threads

- Kernel unaware of threads – no modification required
- Run-time system or thread manager
  - A collection of procedures
  - No need to manipulate address space (only kernel can do)
- Each process needs its own thread table
  - Run-time system multiplexes user-level threads on top of “virtual processors”



Implementing threads in user-space

- Pros
  - Thread switch is very fast
  - No need for kernel support
  - Customized scheduler
  - Each process ~ virtual processor
- Cons - ‘real world’ factors
  - Blocking system calls
  - Page faults
  - I/O and multiprogramming

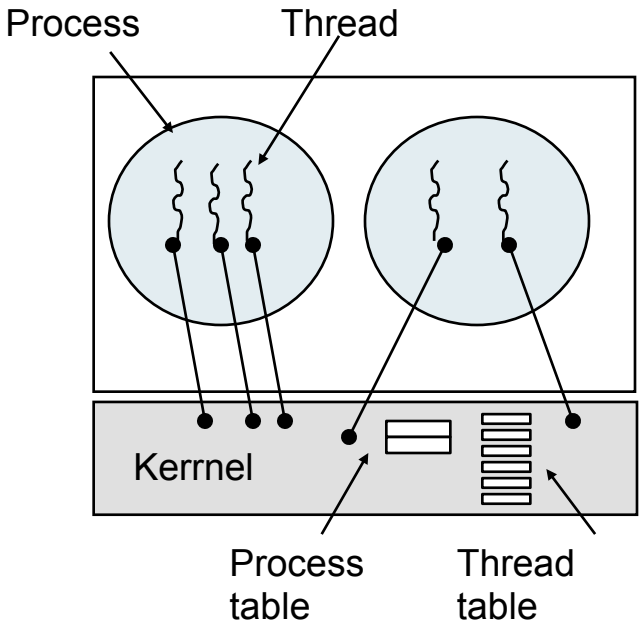


What you see …

And what the kernel sees …

Implementing threads in the kernel

- No need for runtime system
- No wrapper for system calls
- But … creating threads is more expensive
  - Recycle? Mark a destroy thread as not runnable and reuse it later to save overhead
- And system calls are expensive

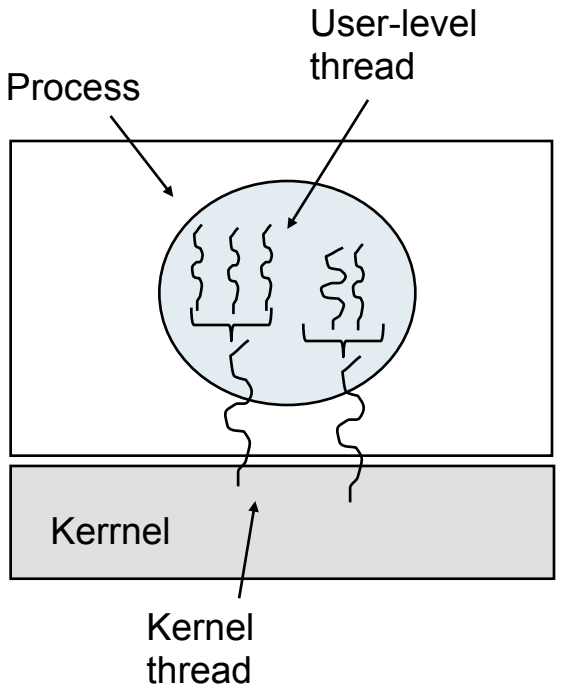


Processes and threads' performance

- On an old 700MHz Pentium running Linux 2.2.*
- Processes
  - fork()/exit() - 251µsec
- Kernel-level thread
  - pthread_create()/pthread_join() - 94µsec (2.6x faster)
- User-level thread
  - pthread_create()/pthread_join() - 4.5µsec (21x faster)

Hybrid thread implementations

- Trying to get the best of both worlds
- Multiplexing user-level threads onto kernel- level threads
- One popular variation – two-level model (you can bound a user-level thread to a kernel one)



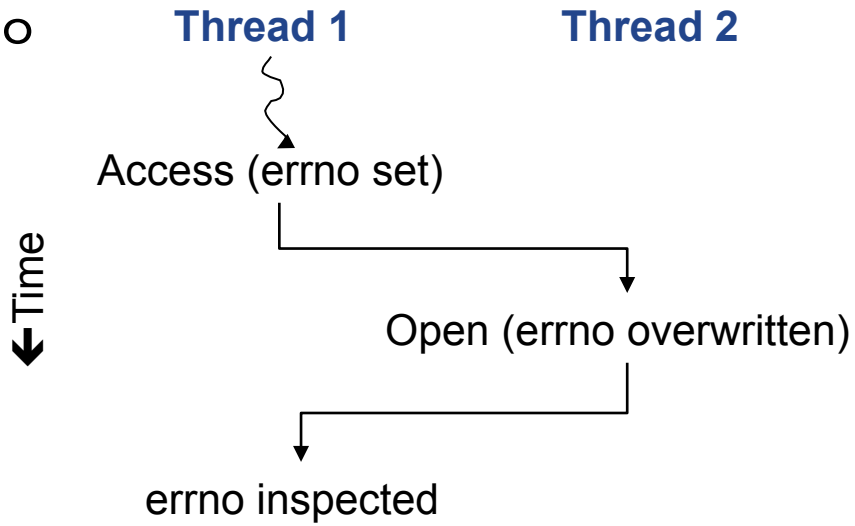
Scheduler activations*

- Goal
  - Functionality of kernel threads &
  - Performance of user-level threads
  - Without special non-blocking system calls
- Problem: needed control & scheduling information distributed bet/ kernel & each app's address space
- Basic idea
  - When kernel finds out a thread is about to block, *upcalls* the runtime system (activates it at a known starting address)
  - When kernel finds out a thread can run again, *upcalls* again
  - Run-time system can now decide what to do
- Pros – fast & smart
- Cons – *upcalls* violate layering approach

*Anderson et al., "Scheduler Activations: effective Kernel Support for the User-level Management of Parallelism," SOSP, Oct. 1991.

Single-threaded to multithreaded

- Threads and global variables
  - An example problem – `errno` when a process makes a syscall that fails, put error code in `errno`



  - Prohibit global variables? Legacy code?
  - Assign each thread its own global variables
    - Allocate a chunk of memory and pass it around
    - Create new library calls to create/set/destroy global variables

Single-threaded to multithreaded

- Many library procedures are not reentrant
- Re-entrant: *able to handle a second call while not done with previous one*

  e.g. assemble msg in a buffer before sending it
- Solutions
  - Rewrite library?
  - Wrappers for each call?

- Semantics of `fork()` & `exec()` system calls
  - Duplicate all threads or single-threaded child?
  - Are you planning to invoke `exec()`?

- Other system calls (closing a file, `lseek`, …?)

Single-threaded to multithreaded

- Signal handling, handlers and masking
  1. Send signal to each thread – too expensive
  2. A master thread per process – asymmetric threads
  3. Send signal to an arbitrary thread (control C?)
  4. Use heuristics to pick thread (SIGSEGV & SIGILL – caused by thread, SIGTSTP & SIGINT – caused by external events)
  5. Create a thread to handle each signal – situation specific
- Stack growth
  - When a process' stack overflows, kernel provides more memory automatically; with multiple threads, multiple stacks
- None of the problem is a showstopper, just a warning when going from single to multithreaded systems

Summary

- You want multiple threads per address space
- Kernel-level threads are
  - More efficient than processes, but
  - Not cheap; all operations require a kernel call and parameter check
- User-level threads are
  - Really fast
  - Great for common-case operations, but
  - Can suffer in uncommon cases due to kernel obliviousness
- Scheduler activations are a good answer

How things start to go wrong …

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

static volatile int counter = 0;

void *
mythread(void *arg)
{
  printf("%s: begin\n", (char*) arg);
  int i;
  for (i = 0; i < 1e7; i++) {
    counter = counter + 1;
  }

  printf("%s: done\n", (char*) arg);
  return NULL;
}

int
main (int argc, char *argv[])
{
  pthread_t p1, p2;
  printf("main: begin (counter = %d)\n", counter);
  pthread_create(&p1, NULL, mythread, "A");
  pthread_create(&p2, NULL, mythread, "B");
  pthread_join(p1, NULL);
  pthread_join(p2, NULL);
  printf("main: done with both (counter = %d)\n", counter);
  return 0;
}
```

```
~/sandbox$ ./sharedCounter
main: begin (counter = 0)
A: begin
B: begin
B: done
A: done
main: done with both (counter = 20000000)
```

```
~/sandbox$ ./sharedCounter
main: begin (counter = 0)
A: begin
B: begin
B: done
A: done
main: done with both (counter = 11353201)
~/sandbox$ ./sharedCounter
main: begin (counter = 0)
A: begin
B: begin
A: done
B: done
main: done with both (counter = 11598589)
```

What's wrong?!

Next time

- Synchronization
  - Race condition & critical regions
  - Software and hardware solutions
  - Review of classical synchronization problems
  - …
- *What really happened on Mars?*
  http://research.microsoft.com/~mbj/Mars_Pathfinder/Mars_Pathfinder.html