Threads

Today

- Why threads?
- Thread model & implementation
- …

Next time

- CPU Scheduling

Concurrency and parallelism

- Many programs need to perform mostly independent tasks that do not need to be serialized, e.g.
  - Web server – multiple requests from clients, updating carts, checking credit card, put a web page reply together, …
  - Text editor – update screen, save file just in case, do spell checking, …
  - 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 exec.; for performance

How can we get this?

- Given the process abstraction as we know it
  - fork several processes
  - cause 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.
- Some 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)

The problem with processes …

- A process consists of (at least):
  - An address space
  - The code for the running program
  - The data for the running program
  - An execution stack and stack pointer (SP)
    - Traces state of procedure calls made
  - The program counter (PC), indicating the next instruction
  - A set of general-purpose processor registers and their values
  - A set of OS resources
    - open files, network connections, sound channels, …
- A lot of concepts bundled together!

The problem with processes

- 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 you'd like to have multiple HW execution states:
  - An execution stack & SP
  - PC indicating the next instruction
  - A set of general-purpose processor registers & their values

The thread model

- Traditionally
  - Process = 1 address space + 1 thread of execution
  - Process = resource grouping + execution stream
    - Resources: program text, data, open files, child processes, pending alarms, accounting info, …
- Key idea with threads
  - Separate the concept of a process (address space, etc.)
  - From that of a minimal “thread of control” (execution state)
  - Threads are concurrent executions sharing an address space (and some OS resources)

Threads and processes

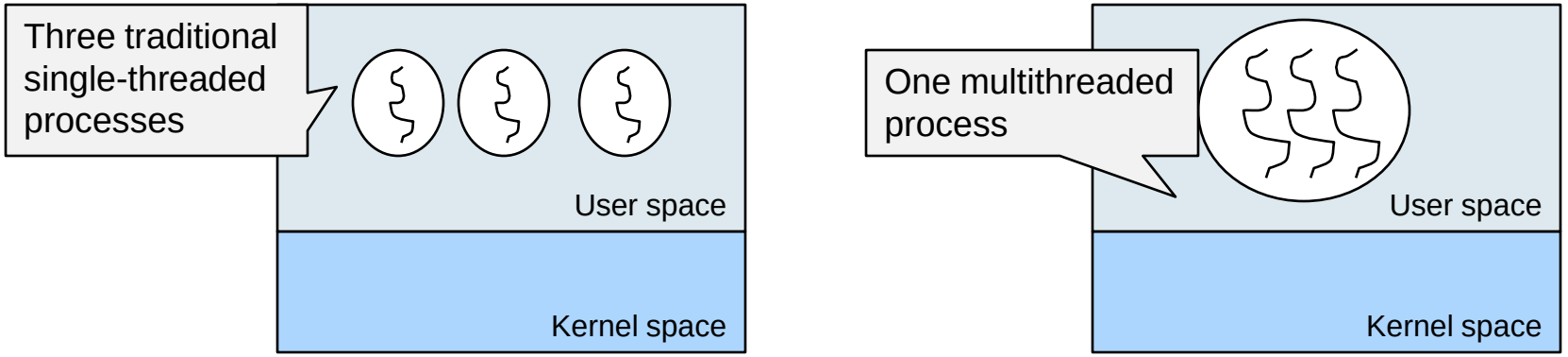
- Most modern OS's support two entities
  - Process – defines the address space and general process attributes
  - Thread – defines a sequential execution stream within a process
- A thread is bound to a process/address space
  - Address space provides isolation
    - If you can't name it, you can't 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

Benefits of threads

- Simpler programming model when application has multiple, concurrent activities
  - Code that deals with asynchronous events can be written with a separate thread to handle each using a synchronous programming model
- Easy/fast to communicate between threads than processes
- Easy/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

The classical thread model

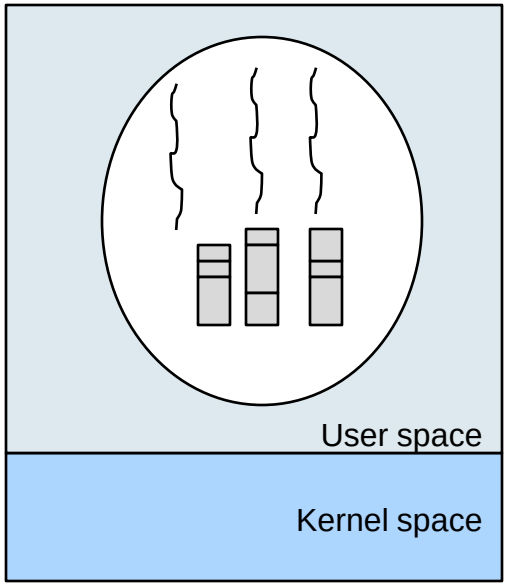
- Threads and processes



- Threads states ~ processes states
- Threads are not as independent as processes
  - They all share the 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, alarms, 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

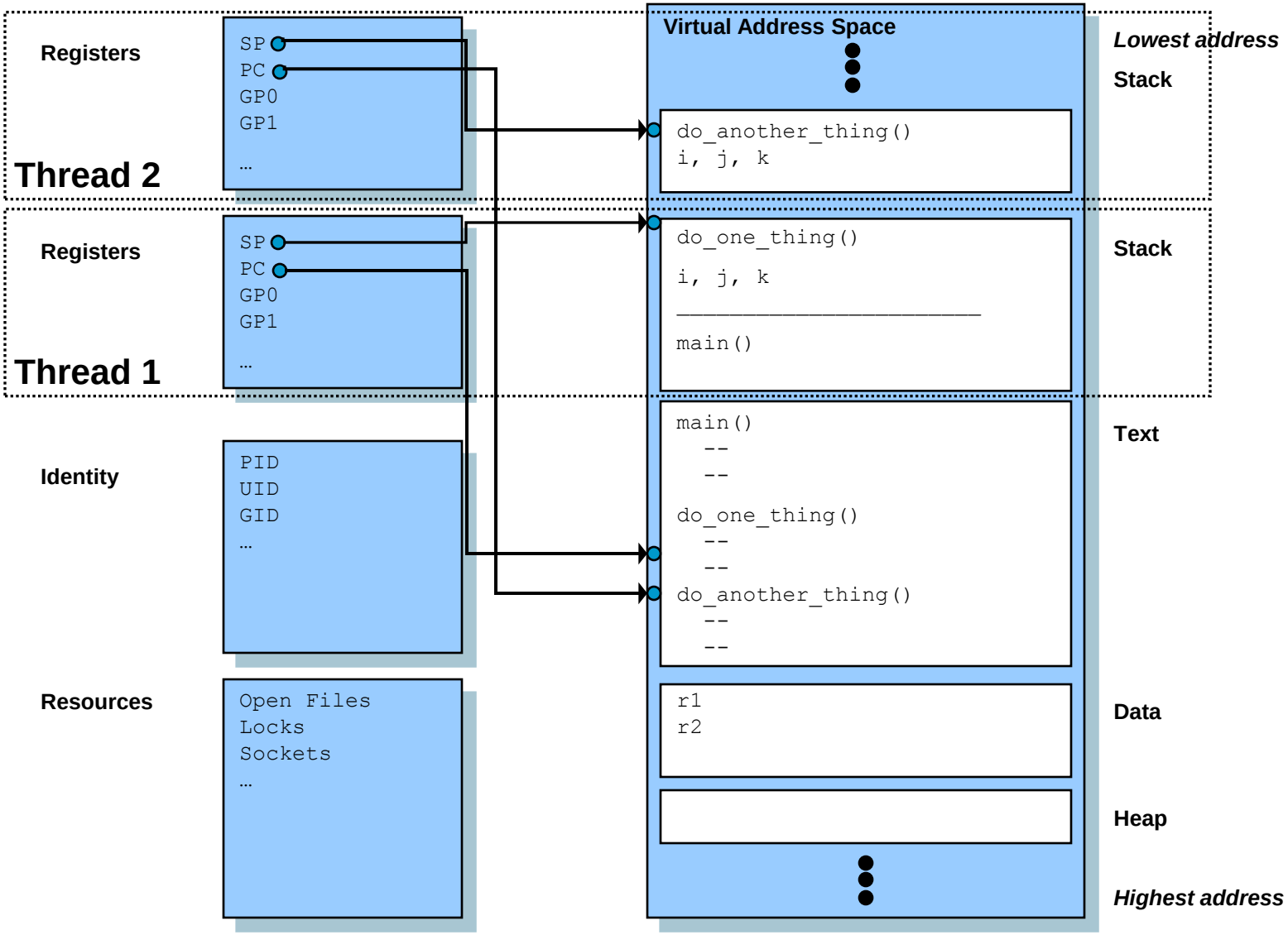
Thread call	**Description**
thread_create	Create a new thread
thread _exit	Terminate the calling thread
thread_join	Wait for a specific thread to exit
thread_yield	Release the CPU to let another thread run

A simple example

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

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

  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, k;

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

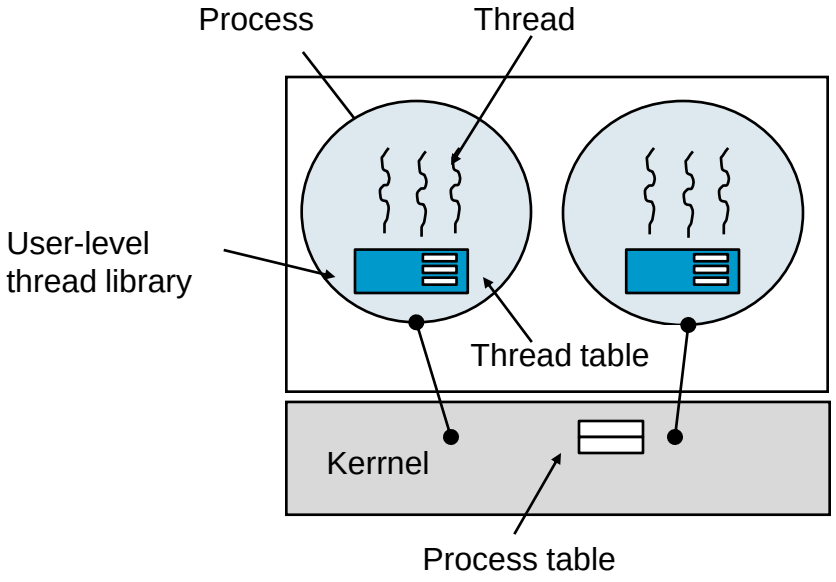
```
void do_wrap_up(int one, int
   another)
{
  int total;
  total = one + another;
  printf("wrap up: one %d, another
    %d and total %d\n", one,
    another, total);
}

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



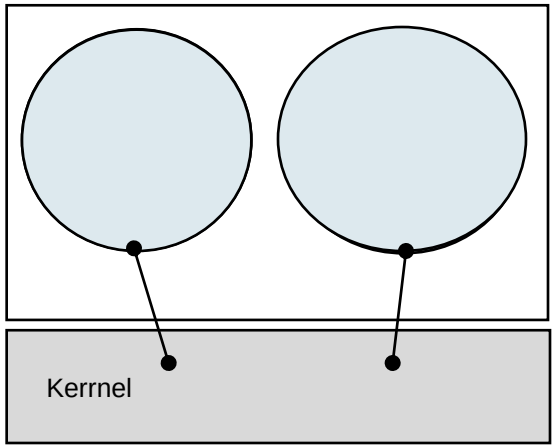
User-level threads

- 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"



User-level threads

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

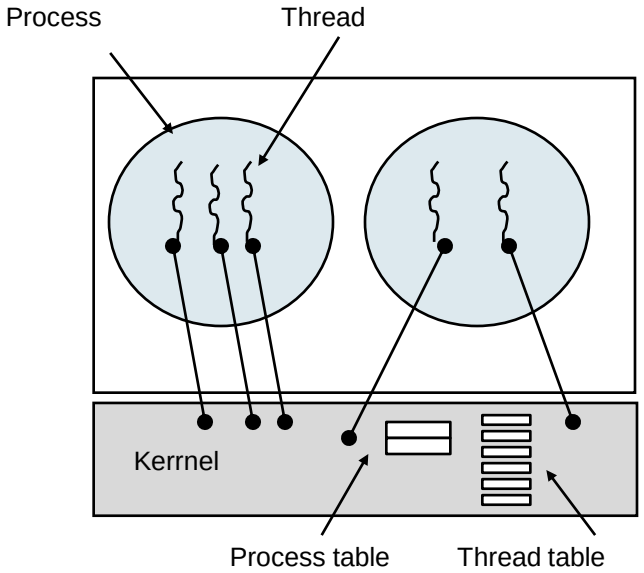


What you see …

And what the kernel sees …

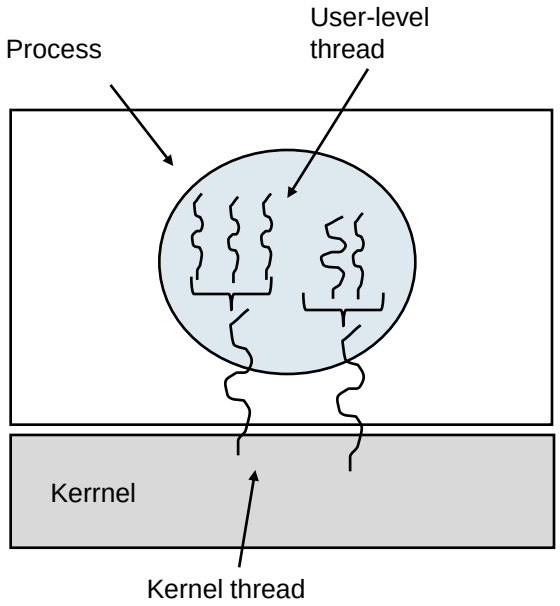
Kernel-level threads

- 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



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)



Processes and threads' performance

Creation time	Process	User-level threads	LWP/Kernel-level threads
SPARCstation 2, Solaris	1700μsec	52μsec (6.7x faster)	350μsec (4.8x faster)
700MHz Pentium, Linux 2.2.*	251μsec fork/exit	4.5μsec create/join (21x faster)	94μsec create/join (2.6x faster)

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.

Thread libraries

- Pthreads – POSIX standard (IEEE 1003.1c) API for thread creation & synchronization
- 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 (1-to-1 in Windows but many-to-many in early Solaris)

POSIX threads

- 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)

Thread call	**Description**
Pthread_create	Create a new thread
Pthread _exit	Terminate the calling thread
Pthread_join	Wait for a specific thread to exit
Phtread_yield	Release the CPU to let another thread run
Pthread_attr_init	Create and initialize a thread's attribute structure
Pthread_attr_destroy	Remove a thread's attribute structure

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! */
```

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

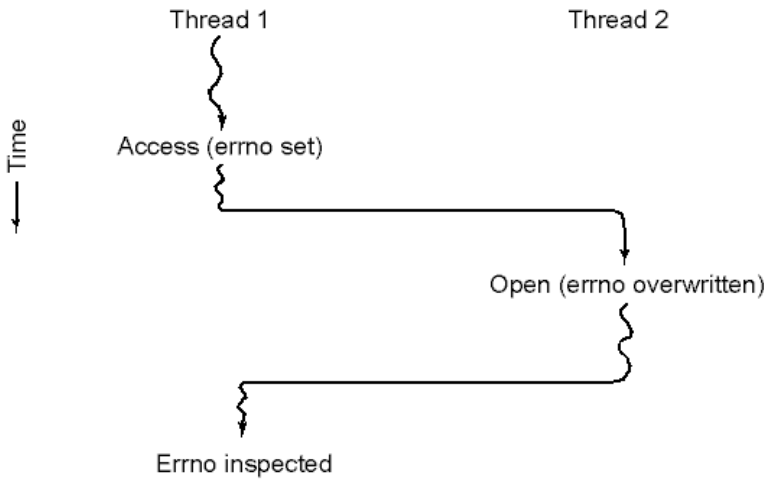
```
int main (int argc, char *argv[])
{
  pthread_t tid;   /* thread id */

  /* 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! */
```

Complications with threads …

- 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, …?)
- 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

Single-threaded to multithreaded

- Threads and global variables
  - An example problem



  - 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?

Summary

- You really 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 verification
- 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
- Next time
  - Multiple processes in the ready queue, but only one processor … which you should you pick next?