System Calls

CPSC 457: Principles of Operating Systems
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Contains slides from Pavol Federl, Mea Wang, Andrew Tanenbaum and Herbert Bos, Silberschatz, Galvin and Gagne

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Topics

- processes vs. threads
- cons/pros of threads
- thread pool
- POSIX threads

Threads

Threads TL;DR

- threads are similar to processes
- but there are some important differences

- TL;DR
  - threads are **more efficient** than processes
  - threads are **more difficult** to use correctly

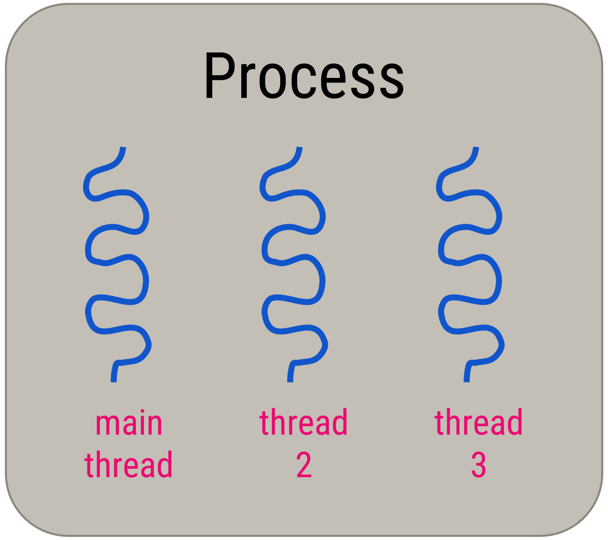
Threads

- just like processes, threads can also be used to express parallelism
- if we need multiple tasks to run concurrently, we can:
  - run each task in separate process; or
  - run each task in separate thread
- if we have enough CPUs, each task can run on separate CPU
- the most common use of threads is to **speed up execution** by allowing programs to utilize multiple CPUs/cores
- programs that use multiple threads are called multi-threaded
- programs that don't use multiple threads are called single-threaded

Threads

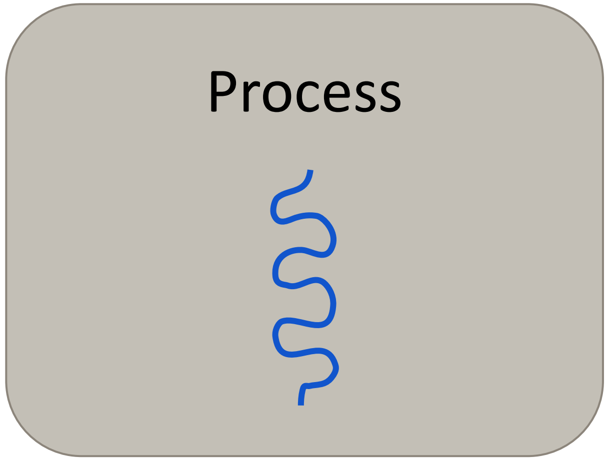
- every process starts with one thread, but can add more threads
  - the original thread is usually called the main thread
  - main thread is the one executing `main()`
- a thread cannot exist without a process
- a process acts like a container for all its threads
- all threads within one process **share the resources** of the process
- threads are scheduled and execute independently

- analogies:
  - multiple VMs share resources of the host computer
  - multiple processes share the resources of the OS



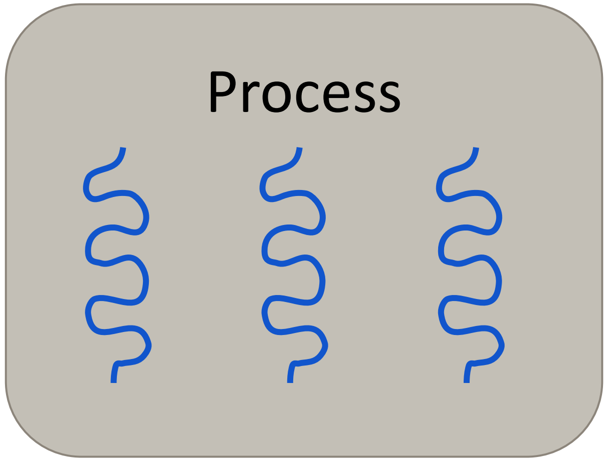
Process with 1 thread (single-threaded process)

- think of a process as a way to group related resources together
  - e.g. address space (heap, global variables, etc), open files, sockets, child processes, signal handlers, accounting info
- a process also has aa "thread of execution"
  - consisting of registers, stack and state
- every process starts with a single thread of execution

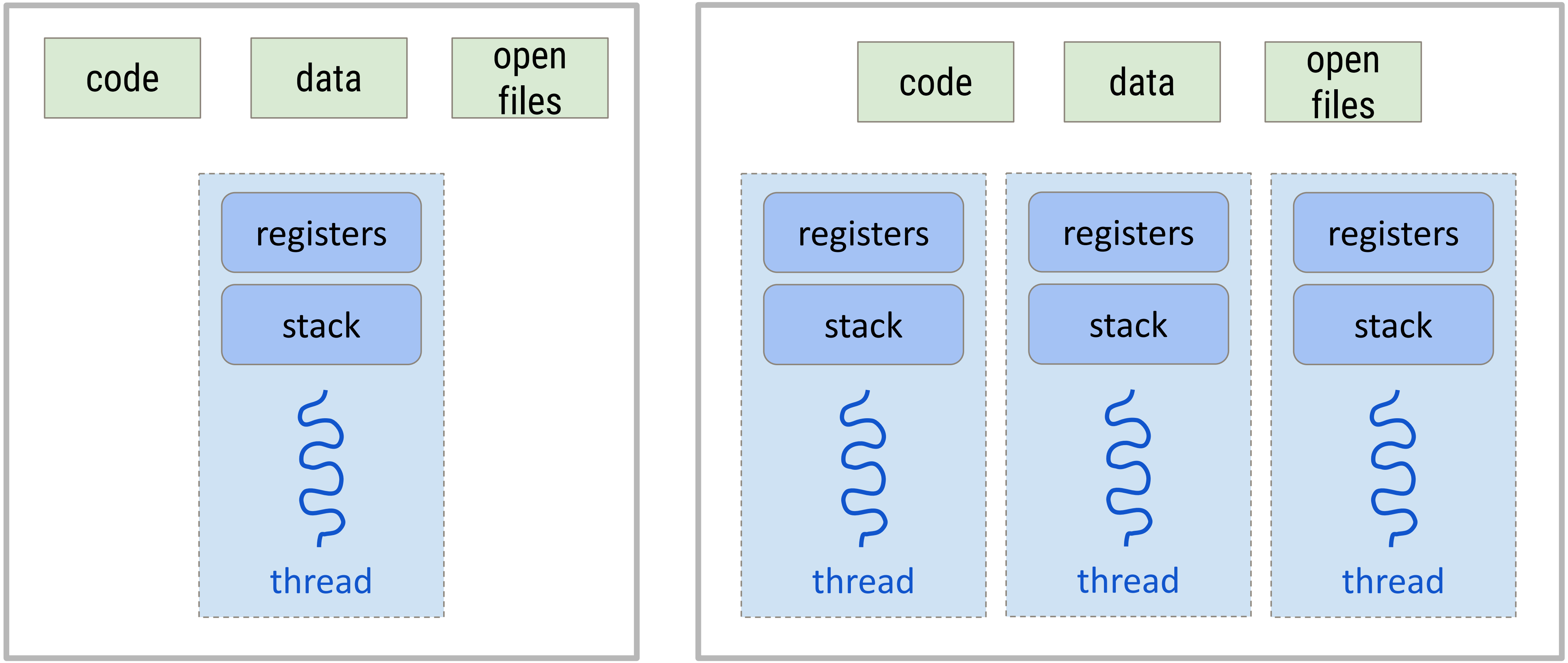


Process with many threads

- any process can create additional thread(s)
- threads allow **multiple executions** to take place within one process environment
- think of threads as multitasking within one process
- all threads execute simultaneously, and are scheduled independently
- threads can make system calls simultaneously
- a thread can share many/most resources with other threads in the same process
- threads belonging to different processes do not share anything



Single-threaded v.s. multi-threaded processes



single-threaded process

multi-threaded process

Process and thread items

Per-process items shared by threads	Per-thread items not shared by threads
address space	PC
global variables	registers
heap	stack
open files	state
child processes	local variables
accounting information	...
signals	
...	

For example...

- if one thread opens a file, all* threads can read and write to it (but very carefully)
- if one thread changes a global variable, the change will be visible in all* other threads
- if one thread calls `exit()`, all* threads will be killed (*all thread in the same process)

Why Threads

Why threads?

- multithreaded applications could run faster on computers with multiple CPUs/cores
  - by dividing work into tasks and then running tasks in separate threads
  - with N cpus/cores, the optimum speedup is N
- threads can be used to parallelize I/O
  - e.g. 2 threads, each reading a different file
- threads can be used to write responsive GUI applications
  - one UI thread + many worker threads executing lengthy operations, such as I/O requests
  - example: browser running Discord in one tab and YouTube video in another
- using multiple threads can sometimes lead to simpler design
  - e.g. threads can be used to avoid using non-blocking, asynchronous I/O with callbacks and/or complicated state machines

Why threads?

- compared to processes, threads …
  - are "lighter weight"
  - use less memory
  - usually faster to create and destroy
  - have more* options for communication via shared memory
  - can be context-switched more efficiently

Why not threads?

- if a thread misbehaves or crashes, the whole process could misbehave or crash
- programming with threads is more difficult than with processes, because we have to worry about things like:
  - race conditions
  - deadlocks
  - starvation
- to deal with the above, we need to learn:
  - synchronization mechanisms (e.g. mutexes, spinlocks, barriers)
  - atomic operations
  - deadlock avoidance techniques

Thread Example

Thread example: static web server

- web server accepts page requests from browsers and sends replies (pages) back

- handling of each request could be broken down into 3 tasks:
  - receiving request
  - locating and reading the corresponding file on disk
  - sending the page back to browser

- how can we write a server that can handle as many requests per second as possible?
  - buy faster hardware
  - use non-blocking system calls
  - use threads

Thread example: static web server

- using threads to speed up the web server

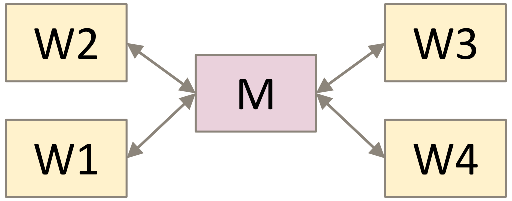
- option 1 – small improvement
  - we treat the tasks as a parallel pipeline with 3 stages
  - we create 3 threads: one for receiving requests, one for fetching results, one for sending pages
  - up to 3x speedup, providing all 3 stages take same amount of time
  - not enough speedup for modern hardware, e.g. 16 core CPU, few SSD disks

- option 2 – much better improvement
  - create separate thread for each request
  - each thread completes 1 request from start to finish (receive, fetch, send)
  - can you guess what the issues might be with this approach?

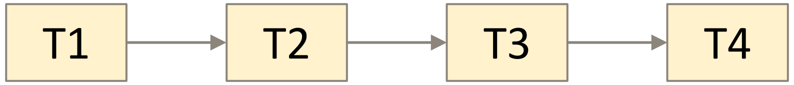
Thread Communication

Common thread communication scenarios

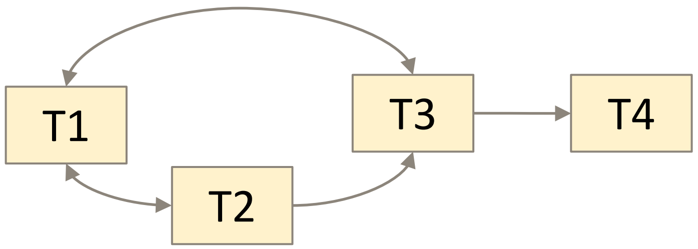
- **manager/worker (**aka master/slave)
  - one manager thread assigns work to worker threads
  - typically manager thread handles all I/O
  - number of worker threads can be static or dynamic



- **pipeline**
  - a task is broken into a series of stages,
    where output of stage (i) is input to to stage (i+1)
  - each stage handled by a different thread



- **other**
  - there a many other more sophisticated ways of organizing threads
  - eg. thread pool, producer/consumer



Thread Pools

Thread pool

- recall the web-server example
  - when server receives a request, it creates a separate thread to handle the request
  - once request is handled, thread is destroyed

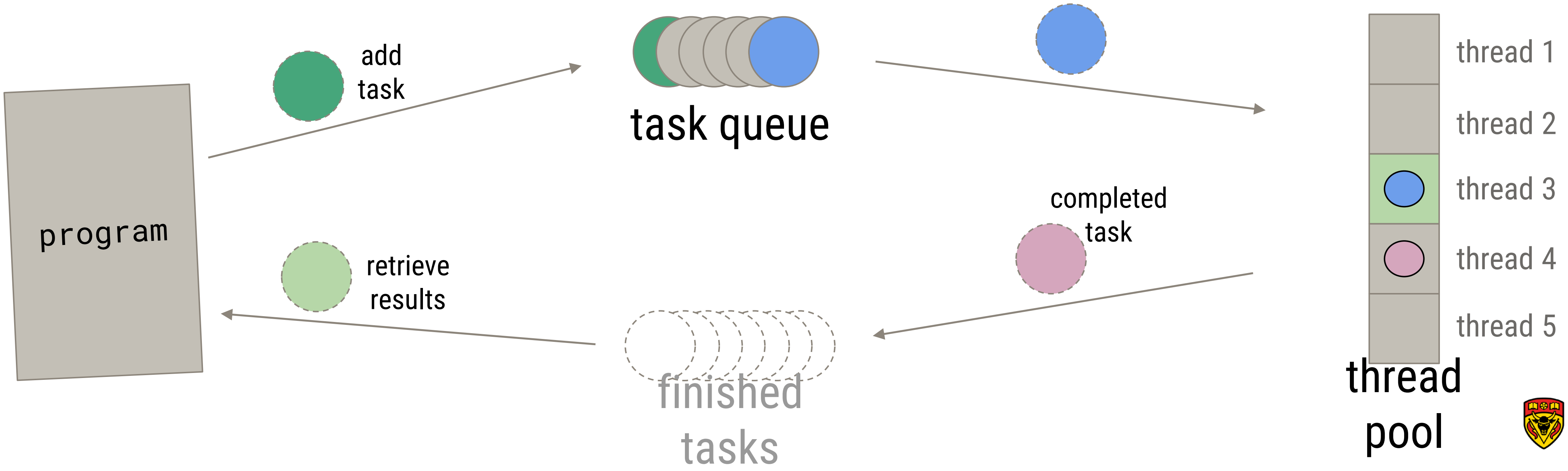
- issues:
  - frequent thread creation and termination → performance problem
  - potentially large number of concurrent threads → resource problem

Thread pool

- **thread pool** — a software design pattern allowing thread recycling/re-use
- main thread creates and maintains a pool of worker threads
- pool size can be tuned, e.g. to the available computing resources, number of cores, ...
- when program needs a thread, it is borrows one of the worker threads from the pool
- when worker thread is done, program returns it back to the pool
- benefits:
  - thread creation/destruction costs are minimized
  - maximum number of concurrent threads is limited
- problems:
  - what if the program needs more threads than the size of the pool?

Thread pool + task queue

- thread pools are usually combined with task queues
- when a program needs to execute task in parallel, instead of asking for a thread, it inserts the task into a task queue
- thread pool monitors the task queue, and next available thread takes task from the task queue, and finishes it
- task queues could implement advanced features, such as priorities and dependencies



Thread Libraries

Thread libraries

- a thread library provides the programmer with an API for creating and managing threads
- a thread library typically contains higher level wrappers around low level system calls
- examples
  - POSIX threads, a.k.a. pthreads (mostly for UNIX)
  - C++ threads (portable)
  - Win32
  - Java

POSIX threads (pthreads)

- to use POSIX threads
  - □ `#include <pthread.h>`
  - compile with `-pthread` (on older g++ compilers use `-lpthread`)
- `pthread_create(*threadid, attr, start_routine, arg);`
  - starts a thread and calls `start_routine(arg)` in new thread; similar to `fork()`
  - each thread gets unique `threadid`, which we need to keep
- `pthread_exit(status);`
  - terminates the current thread, similar to `exit()`, or you can `return` from `start_routine`
- `pthread_join(threadid, *status);`
  - blocks the calling thread until the specified thread terminates, similar to `wait()`
- `pthread_attr_init(attr)` and `pthread_attr_destroy(attr);`
  - initializes / destroys thread attributes
  - these can be fine-tuned with `pthread_attr_set_?()` functions

Example: multithreaded "Hello world"

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

void * task(void *) {
  /* this runs in new thread */
  slow_printf("Hello\n");
  pthread_exit(0); // or return 0;
}

int main() {
  pthread_t tid;
  pthread_create(&tid, NULL, task, NULL);
  /* this runs in original (main) thread */
  slow_printf("world\n");
  pthread_join(tid, NULL);
  printf("Done\n");
}
```

Compile with:

```
$ gcc -pthread main.c
```

Possible outputs:

```
Hello
world
Done
```

```
world
Hello
Done
```

```
wHoerllldo

Done
```

https://replit.com/@jonathanwhudson/hello-world-1

Shared Variables

Multithreading & shared (global) variables

- since address space is shared between threads, all global variables are shared by default
- if one thread changes a global variable, it changes for all threads
- this is very different behavior from multi-process programs (where we used `fork`)

Processes & global variables

```c
int x; /* global variable */

void do_something() {
    x = 11;
    exit(0);
}

int main() {
    x = 10;
    int pid = fork();
    if( pid == 0) {
        do_something();
    }
    else {
        while( wait(NULL) != -1);
    }
    printf("x=%d\n", x);
}
```

Output:

```
$ ./a.out
???
```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Processes & global variables

```
int x; /* global variable */

void do_something() {
    x = 11;
    exit(0);
}

int main() {
    x = 10;
    int pid = fork();
    if( pid == 0) {
        do_something();
    }
    else {
        while( wait(NULL) != -1);
    }
    printf("x=%d\n", x);
}
```

Output:

```
$ ./a.out
x = 10
```

https://repl.it/Lulm/1

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Threads & global variables

```c
int x; /* global variables are shared between threads
!!! */

void * do_something(void *) {
    x = 11;
    pthread_exit(0); // or return 0;
}

int main() {
    x = 10;
    pthread_t tid;
    pthread_create( & tid, NULL, do_something, NULL);
    pthread_join( tid, NULL);
    printf("x=%d\n", x);
}
```

```
Output:

$ gcc -pthread
thread.c
$ ./a.out
???
```

Threads & global variables

```
int x; /* global variables are shared between threads
!!! */

void * do_something(void *) {
    x = 11;
    pthread_exit(0); // or return 0;
}

int main() {
    x = 10;
    pthread_t tid;
    pthread_create( & tid, NULL, do_something, NULL);
    pthread_join( tid, NULL);
    printf("x=%d\n", x);
}
```

Output:

```
$ gcc -pthread
thread.c
$ ./a.out
x = 11
```

https://repl.it/LuoF/0

Creating Multiple Threads

Creating variable number of threads

- how do we create multiple threads?
- we need to keep track of all thread IDs that we create, so that we can join the threads later
- we'll need an array to store these

Example with multiple threads

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

#define NUMBER_OF_THREADS 5

void * thread_print(void * tid) {
  printf("thread %ld running\n", (long int) tid);
  pthread_exit(0);
}

int main() {
  pthread_t threads[NUMBER_OF_THREADS];
  for ( long i = 0; i < NUMBER_OF_THREADS; i++) {
    printf("creating thread %ld\n", (long int) i);
    long status = pthread_create(&threads[i], NULL, thread_print, (void *) i);
    if (status != 0) {
      printf("Oops, pthread_create returned error code %ld\n", status);
      exit(-1);
    }
  }
  for (i = 0; i < NUMBER_OF_THREADS; i++)
    pthread_join(threads[i], NULL);
  return 0;
}
```

Compile with:

```
$ gcc -pthread thread.c
```

Can you guess the output?

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

#define NUMBER_OF_THREADS 5

void * thread_print(void * tid) {
  printf("thread %ld running\n", (long int) tid);
  pthread_exit(0);
}

int main() {
  pthread_t threads[NUMBER_OF_THREADS];
  for ( long i = 0; i < NUMBER_OF_THREADS; i++) {
    printf("creating thread %ld\n", (long int) i);
    long status = pthread_create(&threads[i], NULL, thread_print, (void *
    if (status != 0) {
      printf("Oops, pthread_create returned error code %ld\n", status);
      exit(-1);
    }
  }
  for (i = 0; i < NUMBER_OF_THREADS; i++)
    pthread_join(threads[i], NULL);
  return 0;
}
```

Possible output:

```
$ ./a.out
creating thread 0
creating thread 1
thread 0 running
creating thread 2
creating thread 3
thread 2 running
thread 1 running
creating thread 4
thread 3 running
thread 4 running
```

Other possible outputs:

https://repl.it/Luid/0

Passing multiple parameters to threads & retrieving results

- pthread interface only allows a single parameter to be passed to the thread function
- lucky for us, the parameter is a void pointer (`void*`), a generic pointer
- we can use it to pass any number of parameters, and even use it to return results
- a common design pattern is to create an array of struct, one for each thread
- let's say we want N threads to compute `result = a + b * c` for different values of `a`, `b` and `c`

```
#define N 5
struct TMem {
  int a, b, c;   // inputs
  int result;    // outputs
  pthread_t tid;
} tarr[N];
```

- then we can pass a pointer to different elements of this array to each thread
- basically, each thread will get its own dedicated area of memory

allocate separate memory for each thread, including input parameters and result

```c
#define NUMBER_OF_THREADS 5
struct TMem {
  pthread_t tid;
  int a, b, c, result;
} tarr[NUMBER_OF_THREADS];

void * calc(void * targ) {
  struct TMem * tm = (struct TMem *) targ;
  tm-> result = tm->a + tm->b * tm->c;
  return 0;
}

int main() {
  for (int i = 0; i < NUMBER_OF_THREADS; i++) {
    tarr[i].a = i; tarr[i].b = i + 1; tarr[i].c = i + 2;
    if( 0 != pthread_create(& tarr[i].tid, 0, calc, & tarr[i])) {
      printf("Error: pthread_create failed\n"); exit(-1);
    }
  }
  for (int i = 0; i < NUMBER_OF_THREADS; i++) {
    pthread_join(tarr[i].tid, 0);
    printf("%d + %d * %d = %d\n",
      tarr[i].a, tarr[i].b, tarr[i].c, tarr[i].result);
  }
}
```

```
$ gcc -l pthread thread.c
$ ./a.out
0 + 1 * 2 = 2
1 + 2 * 3 = 7
2 + 3 * 4 = 14
3 + 4 * 5 = 23
4 + 5 * 6 = 34
```

https://repl.it/@jonathanwhudson/simple-threads-1

C++ Threads

C++ threads

```
#include <iostream>
#include <thread>

int x = 10;

void do_something() {
  x = 11;
}

int main() {
  auto t1 = std::thread( do_something );
  t1.join();
  std::cout << "x = " << x << "\n";
}
```

```
$ g++ -pthread thread.cpp
$ ./a.out
x = 11
```

https://repl.it/@jonathanwhudson/global-variable

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C++ threads – passing parameters by value

```
#include <cstdio>
#include <thread>
#include <chrono>
#include <string>

void task(std::string task_name, int start, int end) {
  for( int i = start ; i < end ; i ++ ) {
    printf("Thread '%s': i=%d\n", task_name.c_str(), i);
    std::this_thread::sleep_for(
      std::chrono::milliseconds(1));
  }
}

int main() {
  auto t1 = std::thread( task, "t1", 0, 3);
  auto t2 = std::thread( task, "thread 2", 100, 105);
  t1.join();
  t2.join();
}
```

```
$ g++ -pthread thread.cpp
$ ./a.out
Thread 't1': i=0
Thread 'thread 2': i=100
Thread 't1': i=1
Thread 'thread 2': i=101
Thread 't1': i=2
Thread 'thread 2': i=102
Thread 'thread 2': i=103
Thread 'thread 2': i=104
```

https://repl.it/@jonathanwhudson/c-threads-with-parameters

C++ threads – parameters (by reference) & retrieving results

```
void sum( int start, int end, int step, int & result)
{
  for( auto i = start ; i < end ; i += step)
    result += i;
}

int main()
{
  constexpr int N = 1024;
  int sum_even = 0, sum_odd = 0;
  std::thread t1(sum, 0, N, 2, std::ref(sum_even));
  std::thread t2(sum, 1, N, 2, std::ref(sum_odd));
  t1.join(); t2.join();
  std::cout << "Sums = " << sum_even << " " << sum_odd << "\n"
            << "Sum = " << sum_even + sum_odd << "\n"
            << "Formula = " << N * (N-1) / 2 << "\n";
}
```

```
Sums = 261632 262144
Sum = 523776
Formula = 523776
```

https://repl.it/@jonathanwhudson/thread-sum

C++ threads – parameters by pointer & retrieving results

```
void sum( int start, int end, int step, int * result)
{
  for( auto i = start ; i < end ; i += step)
    * result += i;
}

int main()
{
  const int N = 1024;
  int sum_even = 0, sum_odd = 0;
  std::thread t1(sum, 0, N, 2, & sum_even);
  std::thread t2(sum, 1, N, 2, & sum_odd);
  t1.join(); t2.join();
  std::cout << "Sums = " << sum_even << " " << sum_odd << "\n"
            << "Sum = " << sum_even + sum_odd << "\n"
            << "Formula = " << N * (N-1) / 2 << "\n";
}
```

```
Sums = 261632 262144
Sum = 523776
Formula = 523776
```

https://repl.it/@jonathanwhudson/thread-sum-2

C++ threads – lambdas [advanced]

```
int main()
{
  const int N = 1024;
  int sum_even = 0, sum_odd = 0;
  std::thread t1( [&] () {
    for( auto i=0 ; i<N ; i+=2)
      sum_even += i;
  });
  std::thread t2( [& sum_odd] () {
    for( auto i=1 ; i<N ; i+=2)
      sum_odd += i;
  });
  t1.join(); t2.join();
  std::cout << "Sums = " << sum_even << " " << sum_odd << "\n"
            << "Sum = " << sum_even + sum_odd << "\n"
            << "Formula = " << N * (N-1) / 2 << "\n";
}
```

```
Sums = 261632 262144
Sum = 523776
Formula = 523776
```

https://repl.it/@jonathanwhudson/thread-sum-with-lambdas

C++ threads – array of threads

```
const int NTHREADS = 5;

void task(int tid)
{
  printf("thread %d running\n", tid);
}

int main()
{
  std::vector<std::thread> threads;
  for( auto i = 0 ; i < NTHREADS ; i ++) {
    printf("creating thread %d\n", i);
    threads.push_back( std::thread(task, i));
  }
  for( auto & t : threads)
    t.join();
}
```

```
creating thread 0
creating thread 1
thread 0 running
creating thread 2
creating thread 3
creating thread 4
thread 4 running
thread 3 running
thread 2 running
thread 1 running
```

https://repl.it/@jonathanwhudson/array-of-threads

Thread Implementations

Thread implementations

- kernel-level threads
  - managed by the kernel/OS
  - most common

- user-level threads
  - entirely implemented in user space
  - kernel knows nothing about threads (i.e. OS does not need to support threads at all)
  - not very common, used in some HPC environments for efficiency

- hybrids
  - very uncommon (HPC?)

Signal Handling

Signal handling

- signal handling is more complicated with threads
  - which thread should handle the signal?
    i.e. in which thread's context should the signal handler be executed?
  - what about user-level threads?
- in POSIX systems, signal delivery depends on the type of the signal:
  - some signals are thread specific:
    - eg. `SIGSEGV` is delivered to the thread that caused the exception
    - `pthread_kill(thread_id, signal)` is only delivered to the target thread
  - most signals are delivered to the process
    - only one thread will handle the signal (usually the main thread, but can be arbitrary)
    - can change which thread handles which signal using `pthread_sigmask()`
- example:
  - default behavior of <ctrl-c> → `SIGINT`, kills all threads

Thread Example

Thread example: word processor

- you are editing a document with 1000 pages
- on page 1 you delete a paragraph, then you decide to jump to page 900
- the application will be busy re-formatting the entire document from the first page so that the content on page 900 can be displayed correctly

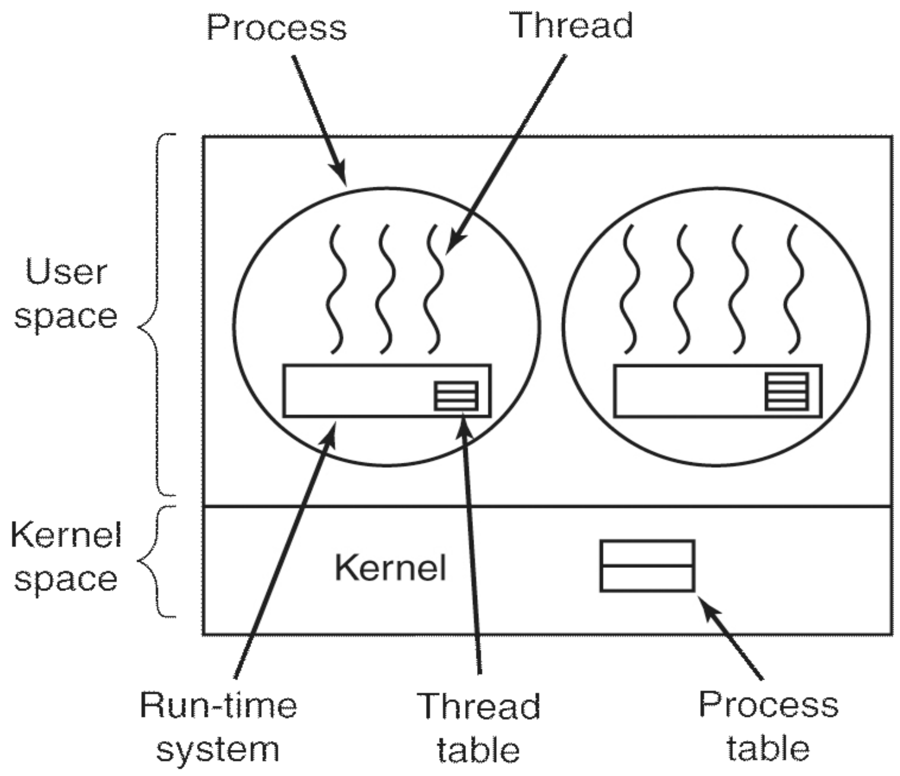
How can threads help?

- one thread for interacting with the user
- one or more threads used for reformatting (to make it run faster on multi-core CPUs)
- one thread for spell checking
- one thread for auto-saving
- ...

User/Kernel Level Threads

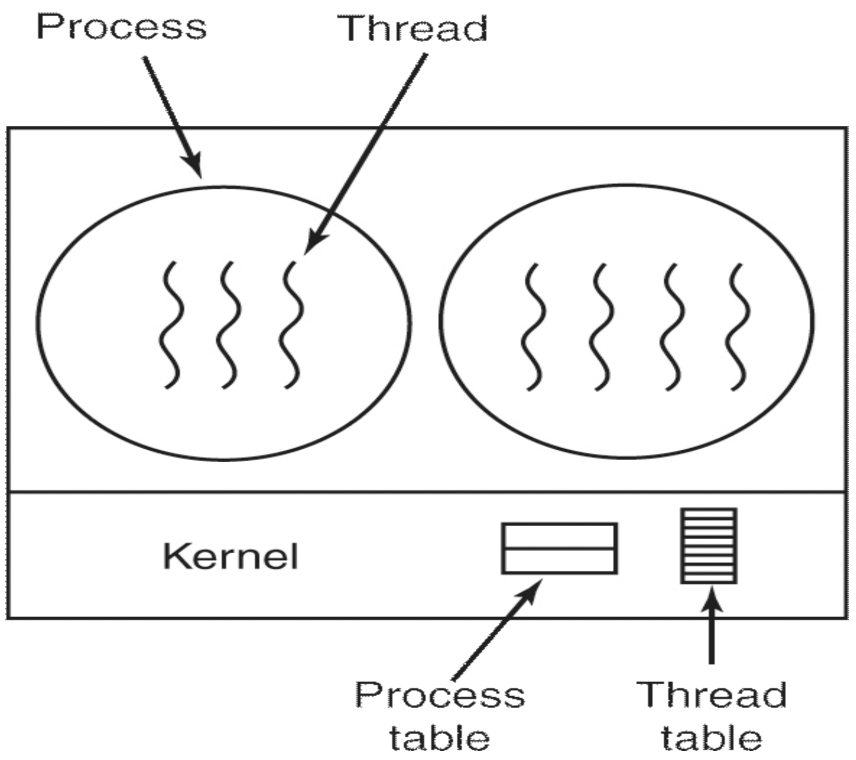
User-level threads

- threads are implemented entirely in user space
- requires no support from OS → can be used on OSes that don't support threads
- each process has its own thread table and scheduler
- threads usually switch only on I/O requests
- no need to trap into kernel when switching threads, so they are very efficient
- allows custom management and scheduling
- requires OS to support non-blocking I/O
- each additional thread makes other threads run slower
- some issues with paging



Kernel-level threads

- one master thread table at the kernel level
- thread creation/deletion/scheduling done in the kernel space
- works well when lot of blocking I/O ops needed
- processes with multiple threads run faster
  - each thread can get same CPU time
- less efficient, since thread operations need to trap into the kernel
- increased kernel complexity

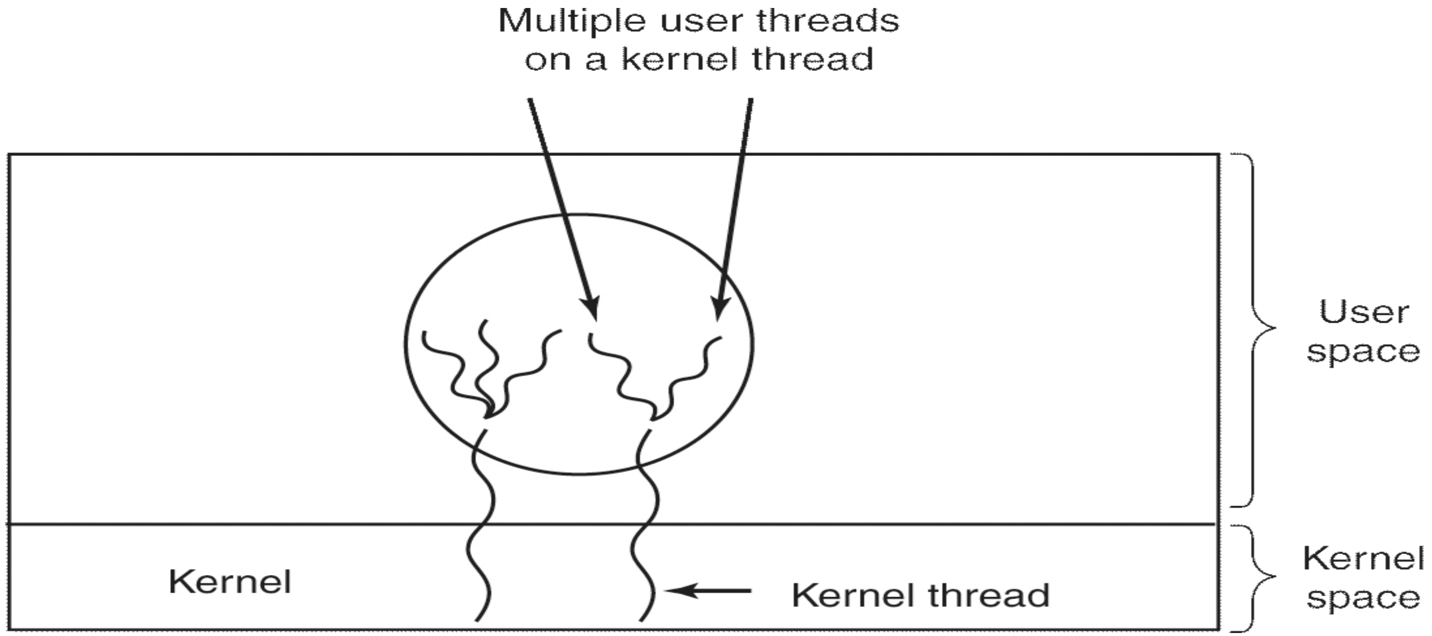


User-level vs kernel-level threads

	Pros	Cons
User level	• no need for OS support • fast context switch • no traps are needed • customized scheduling	• needs non-blocking system calls • a thread may run forever • page faults • inefficient for threads with many blocking procedure/system calls • all threads get one time slice
Kernel level	• blocking calls are no problem • OS aware of all threads → more efficient global scheduling	• some issues around fork() • sending signals to threads

Hybrid

- goal: combining the advantages of user-level threads with kernel-level threads.
- idea: multiplex user-level threads into some or all of the kernel-level threads
  - the kernel is aware of only the kernel-level threads and schedules those
  - the user-level threads are managed in the user space
- it is up to the application to decide how many kernel-level and user-level threads to create
- result: more flexibility



Scheduler Activations

Scheduler activations

- a mechanism to allow closer integration between user-level threads and the kernel
- allows for hybrid kernel-level and user-level threads
- supported by some kernels
- kernel notifies the application when 'interesting' events occur
  - eg. when a thread has been blocked, could deal with page faults
  - the notification is called an **upcall**
  - application can then react by rescheduling its threads

Thread Models

Thread models

- N:1 (many-to-one) or user-level threads
  - many user-level threads per single kernel thread
  - thread management is done by the thread library in the user space
  - E.g., Solaris Green Threads, GNU Portable Threads

- 1:1 (one-to-one) or kernel-level threads
  - maps each user thread to a kernel thread
  - E.g., Windows NT/XP/2000, Linux, Solaris 9 and later

- M:N (many-to-many) or hybrid user/kernel level threads
  - multiplexes many user-level threads to a smaller or equal number of kernel threads
  - eg. Marcel, a multithreading library for HPC

Review

Review

- When the parent process terminates, what happens to its children (UNIX)?
  - https://repl.it/@pavolfederl/GraveExpensiveField
  - but try the same program on your Linux machine
- What could cause a process to change from running state to ready state?
- Why is thread creation faster than process creation?
- What are some of the items that are shared among threads?
- When running multiple threads on a multi-core machine, will all cores be utilized?
- What is the difference between using `pthread_exit()` and `exit()` in a thread?
- Name some pros and cons of implementing threads in user space.

Simple exercise

- write a program that calculates the sum of numbers 1..N
- N will be given on command line
- create 2 threads
  - thread 1:
    - calculates sum of numbers [1 .. N/2)
    - stores result in one global variable
  - thread 2:
    - calculates sum of even numbers [N/2 .. N]
    - stores result in another global variable
- main thread
  - parses command line argument "N"
  - sets 2 global variables to "0" and starts 2 threads
  - waits for both threads to finish
  - sums the two global variables & prints out the result

Summary

- processes vs. threads
- cons/pros of threads
- thread pool
- POSIX threads

Onward to … thread cancellation and race conditions

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