last time

waitpid

- wait for + collect status info of child process
- works regardless of whether child process finished

file descriptors

- table of pointers to files (interpreted broadly)
- conventional numbers for stdin/stdout/stderr
- close: NULL out pointer

dup2: assigning file descriptors

pipe(): get pair of connected file descriptors

anonymous feedback (1)

"I feel like this course could be broken up into two different courses and some of the material (especially OS topics) could be parceled out to a "CSO3" without really duplicating material. When you mentioned last week that this class took parts from comp arch, OS, and networks, that made it clearer to me. It just seems like this class has too much material in it to reasonably cover in one semester. I want to make it very clear that my issue is with how the course is set up, not with you as an instructor–I find your lecturing style to be excellent and engaging, and I think the way CSO2 is set up is also unfair to you. I have found my CSO2 experience to be much worse than my time in CSO1, with all of the difficulty (and more) and none of the payoff. I thought I was prepared for this class, but now I'm seriously concerned about my ability to pass. Could there be any way that the CS department considers splitting this class back into multiple courses for future students?"

anonymous feedback (2)

"Hey professor, you mentioned something a few weeks ago that still kind of sits with me when we were going over one of the quizzes, you said "oh sorry I make so many mistakes because I don't spend much time reviewing/writing these quizzes." I find it really frustrating that you would say and do that when you see students on average spending several hours on each quiz and the average before you curve all your mistakes is like a 60% on each quiz. I don't understand why you would think it's okay to make quizzes take that much time for each student when you clearly aren't interested in putting effort into the quizzes. Thanks"

"spend much time" = hours to write quiz

each quiz generally reviewed by a couple TAs

but one-day turnaround b/c of variation in how far Thurs lecture gets

not like multiple days for final exam

most quiz issues are interpretations I/TA didn't anticipate

lab tomorrow

on synchronization

in-person checkoff only

if can't do that, contact me

why threads?

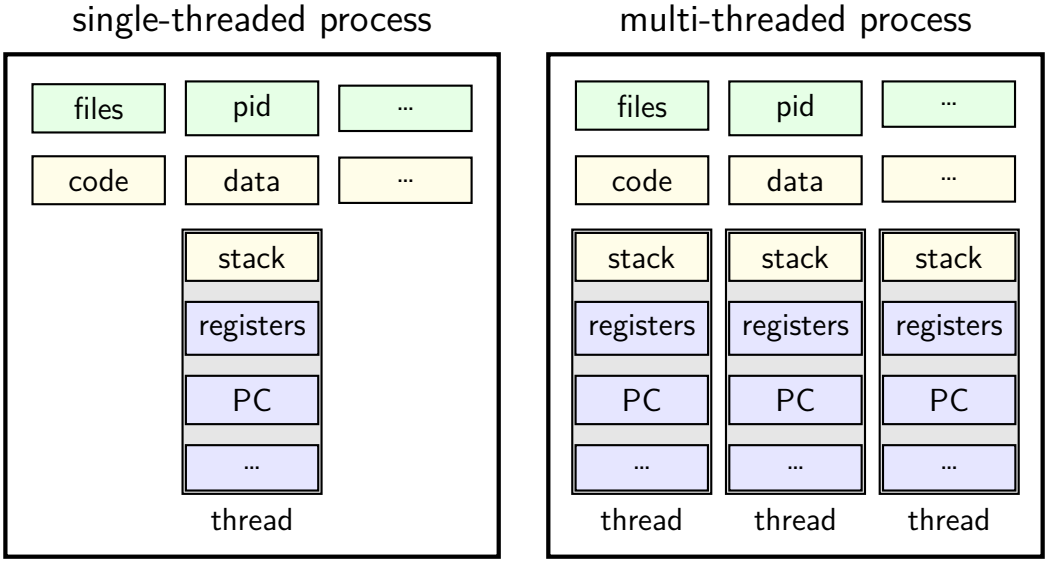
concurrency: different things happening at once

- one thread per user of web server?
- one thread per page in web browser?
- one thread to play audio, one to read keyboard, ...?
- ...

parallelism: do same thing with more resources

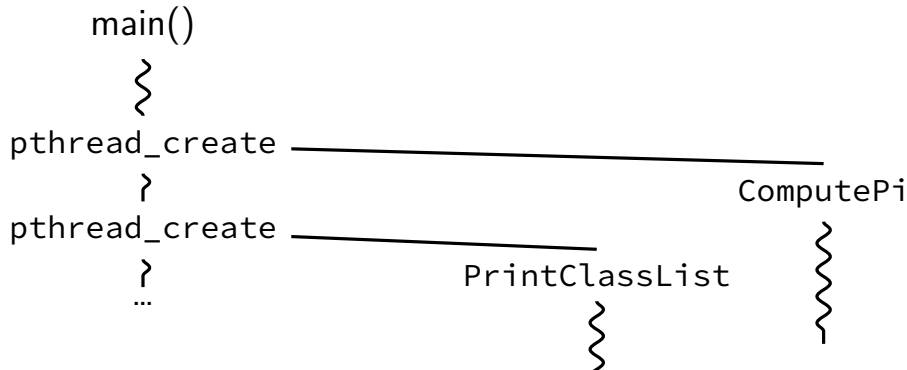
- multiple processors to speed-up simulation (life assignment)

single and multithread processes



pthread_create

```
void *ComputePi(void *argument) { ...  }
void *PrintClassList(void *argument) { ...  }
int main() {
    pthread_t pi_thread, list_thread;
    pthread_create(&pi_thread, NULL, ComputePi, NULL);
    pthread_create(&list_thread, NULL, PrintClassList, NULL);
    ... /* more code */
}
```



pthread_create

```
void *ComputePi(void *argument) { ...  }
void *PrintClassList(void *argument) { ...  }
int main() {
    pthread_t pi_thread, list_thread;
    pthread_create(&pi_thread, NULL, ComputePi, NULL);
    pthread_create(&list_thread, NULL, PrintClassList, NULL);
    ... /* more code */
}
```

pthread_create arguments:

thread identifier

function to run thread starts here, terminates if this function returns

thread attributes (extra settings) and function argument

pthread_create

```
void *ComputePi(void *argument) { ...  }
void *PrintClassList(void *argument) { ...  }
int main() {
    pthread_t pi_thread, list_thread;
    pthread_create(&pi_thread, NULL, ComputePi, NULL);
    pthread_create(&list_thread, NULL, PrintClassList, NULL);
    ... /* more code */
}
```

pthread_create arguments:

thread identifier

function to run thread starts here, terminates if this function returns

thread attributes (extra settings) and function argument

pthread_create

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void *ComputePi(void *argument) { ...  }
void *PrintClassList(void *argument) { ...  }
int main() {
    pthread_t pi_thread, list_thread;
    pthread_create(&pi_thread, NULL, ComputePi, NULL);
    pthread_create(&list_thread, NULL, PrintClassList, NULL);
    ... /* more code */
}
```

pthread_create arguments:

thread identifier

function to run thread starts here, terminates if this function returns

thread attributes (extra settings) and function argument

pthread_create

```
void *ComputePi(void *argument) { ...  }
void *PrintClassList(void *argument) { ...  }
int main() {
    pthread_t pi_thread, list_thread;
    pthread_create(&pi_thread, NULL, ComputePi, NULL);
    pthread_create(&list_thread, NULL, PrintClassList, NULL);
    ... /* more code */
}
```

pthread_create arguments:

thread identifier

function to run thread starts here, terminates if this function returns

thread attributes (extra settings) and function argument

a threading race

```
#include <pthread.h>
#include <stdio.h>
void *print_message(void *ignored_argument) {
    printf("In the thread\n"); return NULL;
}
int main() {
    printf("About to start thread\n");
    pthread_t the_thread;
    pthread_create(&the_thread, NULL, print_message, NULL);
    printf("Done starting thread\n");
    return 0;
}
```

My machine: outputs `In the thread` about 4% of the time.

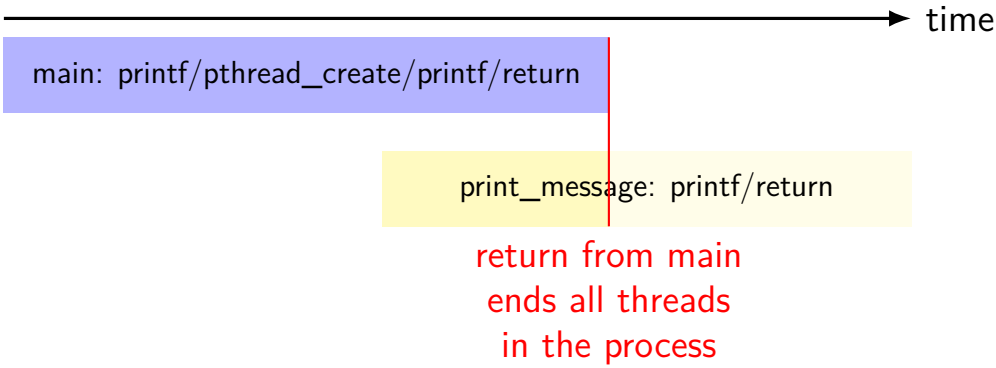
What happened?

a race

returning from main exits the entire process (all its threads)

same as calling exit; not like other threads

race: main's return 0 or print_message's printf first?



fixing the race (version 1)

```
#include <pthread.h>
#include <stdio.h>
void *print_message(void *ignored_argument) {
    printf("In the thread\n");
    return NULL;
}
int main() {
    printf("About to start thread\n");
    pthread_t the_thread;
    pthread_create(&the_thread, NULL, print_message, NULL);
    printf("Done starting thread\n");
    pthread_join(the_thread, NULL);  /* WAIT FOR THREAD */
    return 0;
}
```

fixing the race (version 2; not recommended)

```
#include <pthread.h>
#include <stdio.h>
void *print_message(void *ignored_argument) {
    printf("In the thread\n");
    return NULL;
}
int main() {
    printf("About to start thread\n");
    pthread_t the_thread;
    pthread_create(&the_thread, NULL, print_message, NULL);
    printf("Done starting thread\n");
    pthread_exit(NULL);
}
```

pthread_join, pthread_exit

`pthread_join`: wait for thread, retrieves its return value

- like `waitpid`, but for a thread
- return value is pointer to anything

`pthread_exit`: exit current thread, returning a value

- like `exit` or returning from main, but for a single thread
- same effect as returning from function passed to pthread_create

sum example (only globals)

```
int values[1024];
int results[2];
void *sum_front(void *ignored_argument) {
    int sum = 0;
    for (int i = 0; i < 512; ++i) { sum += values[i]; }
    results[0] = sum;
    return NULL;
}
void *sum_back(void *ignored_argument) {
    int sum = 0;
    for (int i = 512; i < 1024; ++i) { sum += values[i]; }
    results[1] = sum;
    return NULL;
}
int sum_all() {
    pthread_t sum_front_thread, sum_back_thread;
    pthread_create(&sum_front_thread, NULL, sum_front, NULL);
    pthread_create(&sum_back_thread, NULL, sum_back, NULL);
    pthread_join(sum_front_thread, NULL); pthread_join(sum_back_thread, NULL);
    return results[0] + results[1];
}
```

sum example (only globals)

values, results: global variables — shared

```
int values[1024];
int results[2];
void *sum_front(void *ignored_argument) {
    int sum = 0;
    for (int i = 0; i < 512; ++i) { sum += values[i]; }
    results[0] = sum;
    return NULL;
}
void *sum_back(void *ignored_argument) {
    int sum = 0;
    for (int i = 512; i < 1024; ++i) { sum += values[i]; }
    results[1] = sum;
    return NULL;
}
int sum_all() {
    pthread_t sum_front_thread, sum_back_thread;
    pthread_create(&sum_front_thread, NULL, sum_front, NULL);
    pthread_create(&sum_back_thread, NULL, sum_back, NULL);
    pthread_join(sum_front_thread, NULL); pthread_join(sum_back_thread, NULL);
    return results[0] + results[1];
}
```

sum example (only globals)

two different functions
happen to be the same except for some numbers

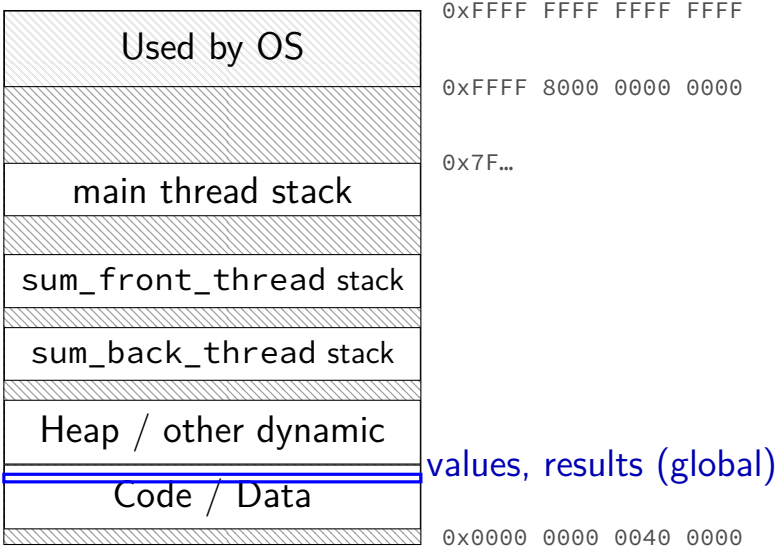
```
int values[1024];
int results[2];
void *sum_front(void *ignored_argument) {
    int sum = 0;
    for (int i = 0; i < 512; ++i) { sum += values[i]; }
    results[0] = sum;
    return NULL;
}
void *sum_back(void *ignored_argument) {
    int sum = 0;
    for (int i = 512; i < 1024; ++i) { sum += values[i]; }
    results[1] = sum;
    return NULL;
}
int sum_all() {
    pthread_t sum_front_thread, sum_back_thread;
    pthread_create(&sum_front_thread, NULL, sum_front, NULL);
    pthread_create(&sum_back_thread, NULL, sum_back, NULL);
    pthread_join(sum_front_thread, NULL); pthread_join(sum_back_thread, NULL);
    return results[0] + results[1];
}
```

sum

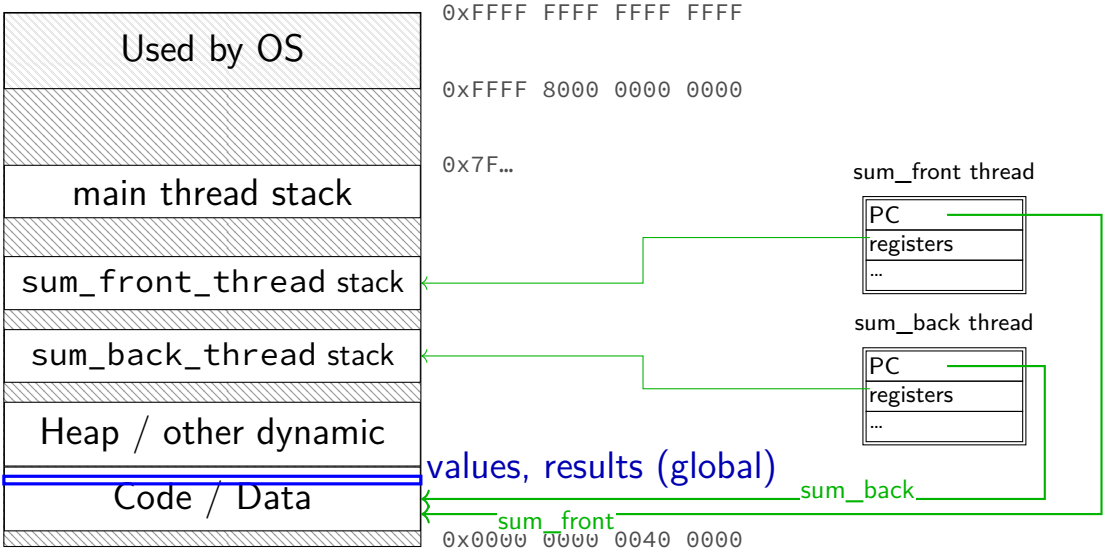
values returned from threads
via global array instead of return value
(partly to illustrate that memory is shared,
partly because this pattern works when we don't join (later))

```
int valu
int resu
void *su
    int
    for (int i = 0; i < 512; ++i) { sum += values[i]; }
    results[0] = sum;
    return NULL;
}
void *sum_back(void *ignored_argument) {
    int sum = 0;
    for (int i = 512; i < 1024; ++i) { sum += values[i]; }
    results[1] = sum;
    return NULL;
}
int sum_all() {
    pthread_t sum_front_thread, sum_back_thread;
    pthread_create(&sum_front_thread, NULL, sum_front, NULL);
    pthread_create(&sum_back_thread, NULL, sum_back, NULL);
    pthread_join(sum_front_thread, NULL); pthread_join(sum_back_thread, NULL);
    return results[0] + results[1];
}
```

thread_sum memory layout



thread_sum memory layout



sum example (to global, with thread IDs)

```
int values[1024];
int results[2];
void *sum_thread(void *argument) {
    int id = (int) argument;
    int sum = 0;
    for (int i = id * 512; i < (id + 1) * 512; ++i) {
        sum += values[i];
    }
    results[id] = sum;
    return NULL;
}
int sum_all() {
    pthread_t thread[2];
    for (int i = 0; i < 2; ++i) {
        pthread_create(&threads[i], NULL, sum_thread, (void *) i);
    }
    for (int i = 0; i < 2; ++i)
        pthread_join(threads[i], NULL);
    return results[0] + results[1];
}
```

sum example (to global, with thread IDs)

```
int values[1024];
int results[2];
void *sum_thread(void *argument) {
    int id = (int) argument;
    int sum = 0;
    for (int i = id * 512; i < (id + 1) * 512; ++i) {
        sum += values[i];
    }
    results[id] = sum;
    return NULL;
}
int sum_all() {
    pthread_t thread[2];
    for (int i = 0; i < 2; ++i) {
        pthread_create(&threads[i], NULL, sum_thread, (void *) i);
    }
    for (int i = 0; i < 2; ++i)
        pthread_join(threads[i], NULL);
    return results[0] + results[1];
}
```

values, results: global variables — shared

sum example (info struct)

```
int values[1024];
struct ThreadInfo {
    int start, end, result;
};
void *sum_thread(void *argument) {
    ThreadInfo *my_info =  (ThreadInfo *) argument;
    int sum = 0;
    for (int i = my_info->start; i < my_info->end; ++i) { sum += values[i]; }
    my_info->result = sum;
    return NULL;
}
int sum_all() {
    pthread_t thread[2]; ThreadInfo info[2];
    for (int i = 0; i < 2; ++i) {
        info[i].start = i*512; info[i].end = (i+1)*512;
        pthread_create(&threads[i], NULL, sum_thread, &info[i]);
    }
    for (int i = 0; i < 2; ++i) { pthread_join(threads[i], NULL); }
    return info[0].result + info[1].result;
}
```

sum example (info struct)

```
int values[1024];
struct ThreadInfo
    int start, end, result;
};
void *sum_thread(void *argument) {
    ThreadInfo *my_info =  (ThreadInfo *) argument;
    int sum = 0;
    for (int i = my_info->start; i < my_info->end; ++i) { sum += values[i]; }
    my_info->result = sum;
    return NULL;
}
int sum_all() {
    pthread_t thread[2]; ThreadInfo info[2];
    for (int i = 0; i < 2; ++i) {
        info[i].start = i*512; info[i].end = (i+1)*512;
        pthread_create(&threads[i], NULL, sum_thread, &info[i]);
    }
    for (int i = 0; i < 2; ++i) { pthread_join(threads[i], NULL); }
    return info[0].result + info[1].result;
}
```

values: global variable — shared

sum example (info struct)

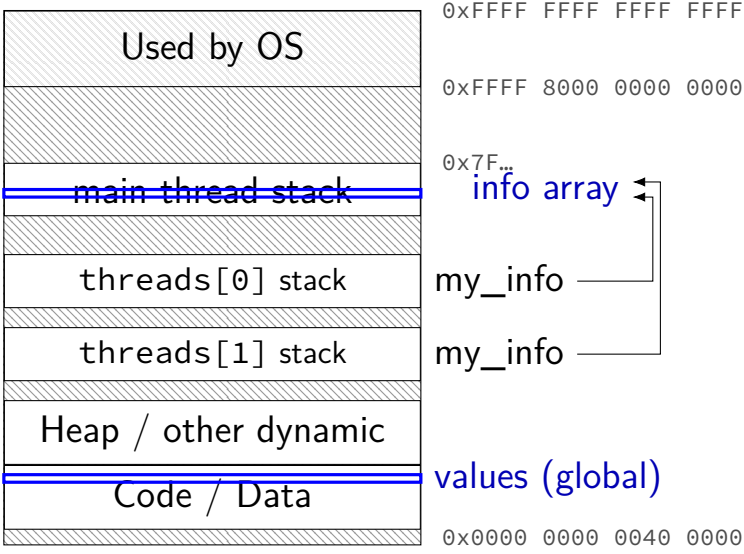
```
int values[1024];
struct ThreadInfo {
    int start, end, result;
};
void *sum_thread(void *argument) {
    ThreadInfo *my_info =  (ThreadInfo *) argument;
    int sum = 0;
    for (int i = my_info->                                    lues[i]; }
    my_info->result = sum;
    return NULL;
}
int sum_all() {
    pthread_t thread[2]; ThreadInfo info[2];
    for (int i = 0; i < 2; ++i) {
        info[i].start = i*512; info[i].end = (i+1)*512;
        pthread_create(&threads[i], NULL, sum_thread, &info[i]);
    }
    for (int i = 0; i < 2; ++i) { pthread_join(threads[i], NULL); }
    return info[0].result + info[1].result;
}
```

my_info: pointer to sum_all's stack
only okay because sum_all waits!

sum example (info struct)

```
int values[1024];
struct ThreadInfo {
    int start, end, result;
};
void *sum_thread(void *argument) {
    ThreadInfo *my_info =  (ThreadInfo *) argument;
    int sum = 0;
    for (int i = my_info->start; i < my_info->end; ++i) { sum += values[i]; }
    my_info->result = sum;
    return NULL;
}
int sum_all() {
    pthread_t thread[2]; ThreadInfo info[2];
    for (int i = 0; i < 2; ++i) {
        info[i].start = i*512; info[i].end = (i+1)*512;
        pthread_create(&threads[i], NULL, sum_thread, &info[i]);
    }
    for (int i = 0; i < 2; ++i) { pthread_join(threads[i], NULL); }
    return info[0].result + info[1].result;
}
```

thread_sum memory layout (info struct)



sum example (to main stack)

```
struct ThreadInfo { int *values; int start; int end; int result };
void *sum_thread(void *argument) {
    ThreadInfo *my_info = (ThreadInfo *) argument;
    int sum = 0;
    for (int i = my_info->start; i < my_info->end; ++i) {
        sum += my_info->values[i];
    }
    my_info->result = sum;
    return NULL;

}
int sum_all(int *values) {
    ThreadInfo info[2]; pthread_t thread[2];
    for (int i = 0; i < 2; ++i) {
        info[i].values = values; info[i].start = i*512; info[i].end = (i+1)*512;
        pthread_create(&threads[i], NULL, sum_thread, (void *) &info[i]);
    }
    for (int i = 0; i < 2; ++i)
        pthread_join(threads[i], NULL);
    return info[0].result + info[1].result;
}
```

sum example (to main stack)

```
struct ThreadInfo { int *values; int start; int end; int result };
void *sum_thread(void *argument) {
    ThreadInfo *my_info = (ThreadInfo *) argument;
    int sum = 0;
    for (int i = my_info->start; i < my_info->end; ++i) {
        sum += my_info->values[i];
    }
    my_info->result = sum;
    return NULL;

}
int sum_all(int *values) {
    ThreadInfo info[2]; pthread_t thread[2];
    for (int i = 0; i < 2; ++i) {
        info[i].values = values; info[i].start = i*512; info[i].end = (i+1)*512;
        pthread_create(&threads[i], NULL, sum_thread, (void *) &info[i]);
    }
    for (int i = 0; i < 2; ++i)
        pthread_join(threads[i], NULL);
    return info[0].result + info[1].result;
}
```

sum example (to main stack)

```
struct ThreadInfo { int *values; int start; int end; int result };
void *sum_thread(void *argument) {
    ThreadInfo *my_info = (ThreadInfo *) argument;
    int sum = 0;
    for (int i = my_info->start; i < my_info->end; ++i) {
        sum += my_info->values[i];
    }
    my_info->result = sum;
    return NULL;

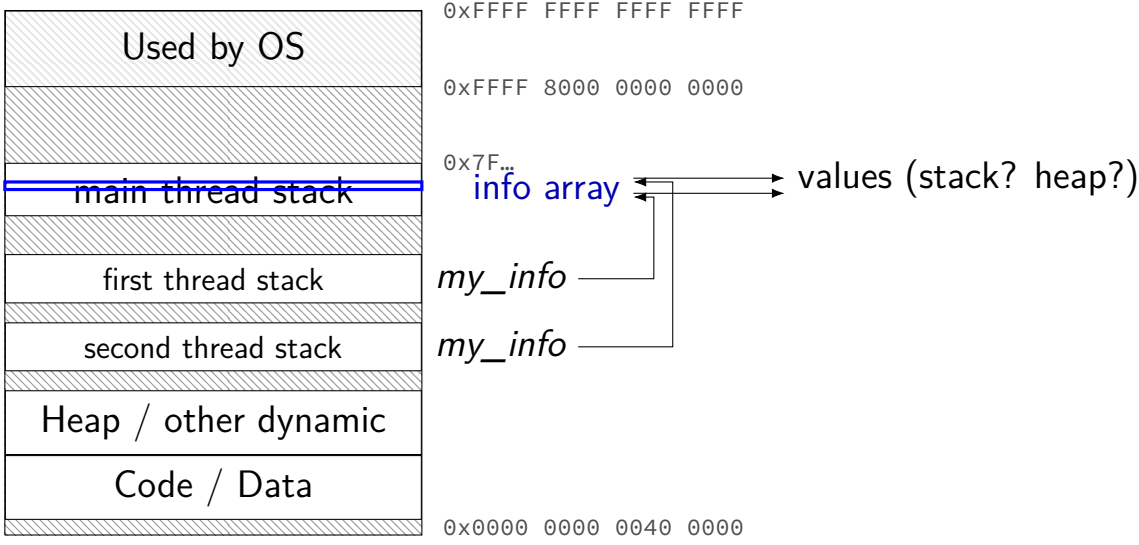
}
int sum_all(int *values) {
    ThreadInfo info[2]; pthread_t thread[2];
    for (int i = 0; i < 2; ++i) {
        info[i].values = values; info[i].start = i*512; info[i].end = (i+1)*512;
        pthread_create(&threads[i], NULL, sum_thread, (void *) &info[i]);
    }
    for (int i = 0; i < 2; ++i)
        pthread_join(threads[i], NULL);
    return info[0].result + info[1].result;
}
```

sum example (to main stack)

```
struct ThreadInfo { int *values; int start; int end; int result };
void *sum_thread(void *argument) {
    ThreadInfo *my_info = (ThreadInfo *) argument;
    int sum = 0;
    for (int i = my_info->start; i < my_info->end; ++i) {
        sum += my_info->values[i];
    }
    my_info->result = sum;
    return NULL;

}
int sum_all(int *values) {
    ThreadInfo info[2]; pthread_t thread[2];
    for (int i = 0; i < 2; ++i) {
        info[i].values = values; info[i].start = i*512; info[i].end = (i+1)*512;
        pthread_create(&threads[i], NULL, sum_thread, (void *) &info[i]);
    }
    for (int i = 0; i < 2; ++i)
        pthread_join(threads[i], NULL);
    return info[0].result + info[1].result;
}
```

program memory (to main stack)



sum example (on heap)

```
struct ThreadInfo { pthread_t thread; int *values; int start; int end; int result
void *sum_thread(void *argument) {
    ...
}

ThreadInfo *start_sum_all(int *values) {
    ThreadInfo *info = new ThreadInfo[2];
    for (int i = 0; i < 2; ++i) {
        info[i].values = values; info[i].start = i*512; info[i].end = (i+1)*512;
        pthread_create(&info[i].thread, NULL, sum_thread, (void *) &info[i]);
    }
    return info;
}

int finish_sum_all(ThreadInfo *info) {
    for (int i = 0; i < 2; ++i)
        pthread_join(info[i].thread, NULL);
    int result = info[0].result + info[1].result;
    delete[] info;
    return result;
}
```

sum example (on heap)

```
struct ThreadInfo { pthread_t thread; int *values; int start; int end; int result
void *sum_thread(void *argument) {
    ...
}

ThreadInfo *start_sum_all(int *values) {
    ThreadInfo *info = new ThreadInfo[2];
    for (int i = 0; i < 2; ++i) {
        info[i].values = values; info[i].start = i*512; info[i].end = (i+1)*512;
        pthread_create(&info[i].thread, NULL, sum_thread, (void *) &info[i]);
    }
    return info;
}

int finish_sum_all(ThreadInfo *info) {
    for (int i = 0; i < 2; ++i)
        pthread_join(info[i].thread, NULL);
    int result = info[0].result + info[1].result;
    delete[] info;
    return result;
}
```

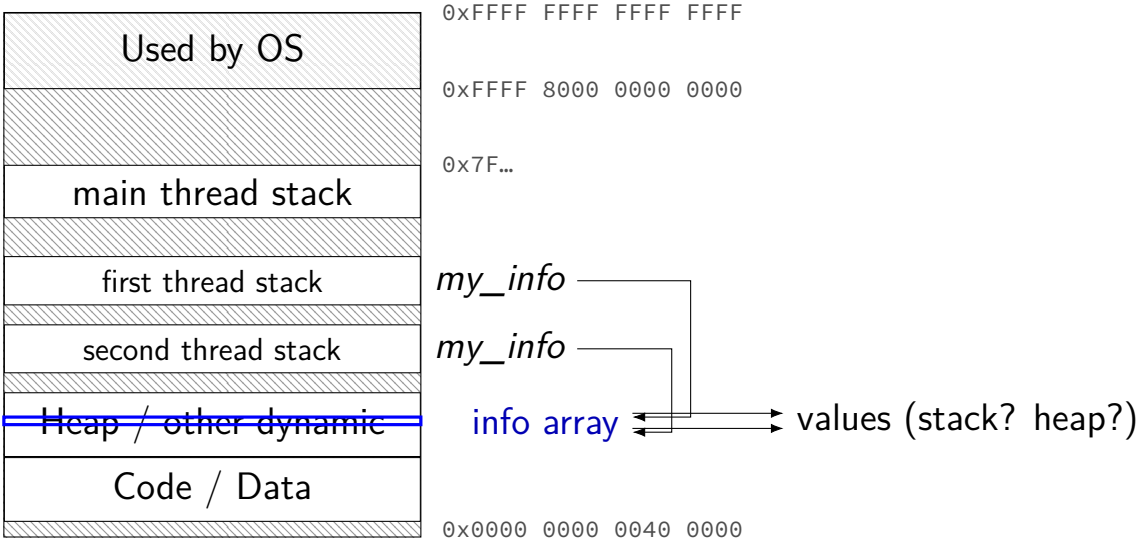
sum example (on heap)

```
struct ThreadInfo { pthread_t thread; int *values; int start; int end; int result
void *sum_thread(void *argument) {
    ...
}

ThreadInfo *start_sum_all(int *values) {
    ThreadInfo *info = new ThreadInfo[2];
    for (int i = 0; i < 2; ++i) {
        info[i].values = values; info[i].start = i*512; info[i].end = (i+1)*512;
        pthread_create(&info[i].thread, NULL, sum_thread, (void *) &info[i]);
    }
    return info;
}

int finish_sum_all(ThreadInfo *info) {
    for (int i = 0; i < 2; ++i)
        pthread_join(info[i].thread, NULL);
    int result = info[0].result + info[1].result;
    delete[] info;
    return result;
}
```

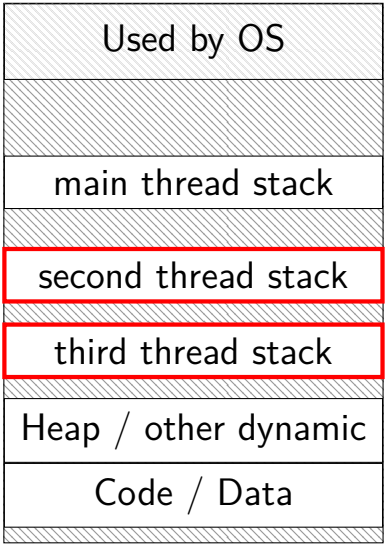
thread_sum memory (heap version)



what's wrong with this?

```
/* omitted: headers */
#include <string>
using std::string;
void *create_string(void *ignored_argument) {
  string result;
  result = ComputeString();
  return &result;
}
int main() {
  pthread_t the_thread;
  pthread_create(&the_thread, NULL, create_string, NULL);
  string *string_ptr;
  pthread_join(the_thread, (void*) &string_ptr);
  cout << "string is " << *string_ptr;
}
```

program memory



0xFFFF FFFF FFFF FFFF

0xFFFF 8000 0000 0000

0x7F…

dynamically allocated stacks

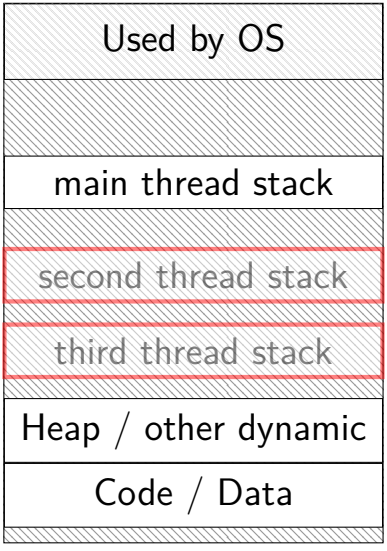
`string result` allocated here

`string_ptr` pointed to here

…stacks deallocated when threads exit/are joined

0x0000 0000 0040 0000

program memory



0xFFFF FFFF FFFF FFFF

0xFFFF 8000 0000 0000

0x7F…

dynamically allocated stacks

`string result` allocated here

`string_ptr` pointed to here

…stacks deallocated when threads exit/are joined

0x0000 0000 0040 0000

thread resources

to create a thread, allocate:

new stack (how big???)

thread control block

deallocated when ...

thread resources

to create a thread, allocate:

new stack (how big???)

thread control block

deallocated when ...

can deallocate stack when thread exits

but need to allow collecting return value

same problem as for processes and waitpid

pthread_detach

```
void *show_progress(void * ...) { ... }
void spawn_show_progress_thread() {
    pthread_t show_progress_thread;
    pthread_create(&show_progress_thread, NULL,
                   show_progress, NULL);

    /* instead of keeping pthread_t around to join thread later: */
    pthread_detach(show_progress_thread);
}

int main() {
    spawn_show_progress_thread();
    do_other_stuff();
    ...
}
```

detach = don't care about return value, etc.
system will deallocate when thread terminates

starting threads detached

```
void *show_progress(void * ...) { ... }
void spawn_show_progress_thread() {
    pthread_t show_progress_thread;
    pthread_attr_t attrs;
    pthread_attr_init(&attrs);
    pthread_attr_setdetachstate(&attrs, PTHREAD_CREATE_DETACHED);
    pthread_create(&show_progress_thread, attrs,
                   show_progress, NULL);
    pthread_attr_destroy(&attrs);
}
```

setting stack sizes

```
void *show_progress(void * ...) { ... }
void spawn_show_progress_thread() {
    pthread_t show_progress_thread;
    pthread_attr_t attrs;
    pthread_attr_init(&attrs);
    pthread_attr_setstacksize(&attrs, 32 * 1024 /* bytes */);
    pthread_create(&show_progress_thread, attrs,
                   show_progress, NULL);
}
```

a note on error checking

from pthread_create manpage:

ERRORS

EAGAIN Insufficient resources to create another thread, or a system-imposed limit on the number of threads was encountered. The latter case may occur in two ways: the **RLIMIT_NPROC** soft resource limit (set via **setrlimit**(2)), which limits the number of process for a real user ID, was reached; or the kernel's system-wide limit on the number of threads, /proc/sys/kernel/threads-max, was reached.

EINVAL Invalid settings in attr.

EPERM No permission to set the scheduling policy and parameters specified in attr.

special constants for *return value*

same pattern for many other pthreads functions

will often omit error checking in slides for brevity

error checking pthread_create

```
int error = pthread_create(...);
if (error != 0) {
    /* print some error message */
}
```

backup slides

thread versus process state

thread state

- registers (including stack pointer, program counter)
- ...

process state

- address space
- open files
- process id
- list of thread states
- ...

process info with threads

parent process info

thread infos	`thread 0: {PC = 0x123456, rax = 42, rbx = …}`
	`thread 1: {PC = 0x584390, rax = 32, rbx = …}`
	…

page tables	
open files	`fd 0: …` `fd 1: …`
…	…

Linux idea: task_struct

Linux model: single "task" structure = thread

pointers to address space, open file list, etc.

pointers can be shared

- e.g. shared open files: open fd 4 in one task → all sharing can use fd 4

`fork()`-like system call "clone": choose what to share

- `clone(0, ...)` — similar to `fork()`
- `clone(CLONE_FILES, ...)` — like fork(), but **sharing** open files
- `clone(CLONE_VM, new_stack_pointer, ...)` — like fork(), but **sharing** address space

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advantage: no special logic for threads (mostly)

- two threads in same process = tasks sharing everything possible

aside: alternate threading models

we'll talk about kernel threads

OS scheduler deals **directly** with threads

alternate idea: library code handles threads

kernel doesn't know about threads w/in process

hierarchy of schedulers: one for processes, one within each process

not currently common model — awkward with multicore