threads 1

which scheduler should I choose?

I care about...

CPU throughput: first-come first-serve

average response time: SRTF approximation

I/O throughput: SRTF approximation

fairness — medium-term CPU usage: something like Linux CFS

fairness — wait time: something like RR

real-world deadlines: earliest deadline first or similar

favoring certain users: strict priority

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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)

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

thread versus process state

thread state — kept in **thread control block**

- registers (including stack pointer, program counter)
- scheduling state (runnable, waiting, ...)
- other information?
- ...

process state — kept in **process control block**

- address space (memory layout, heap location, ...)
- open files
- process id
- list of thread control blocks
- ...

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

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

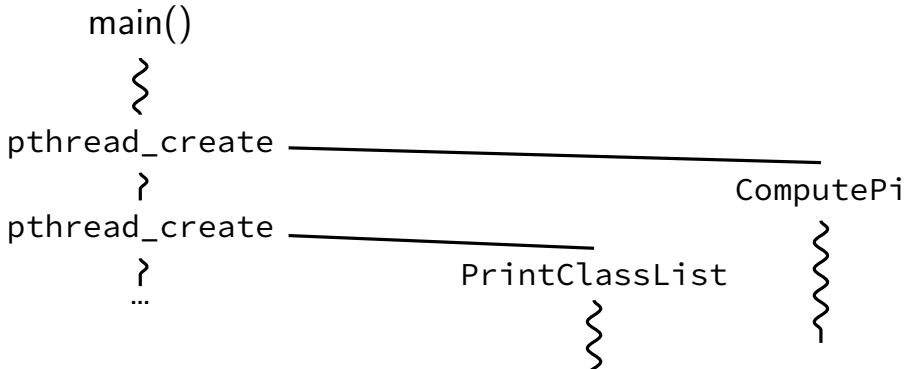
- `clone(0, ...)` — similar to `fork()`
- `clone(CLONE_FILES, ...)` — like fork(), but **sharing** open files
- `clone(CLONE_VM, new_stack_pointer, ...)` — like fork(), but **sharing** address space

advantage: no special logic for threads (mostly)

- two threads in same process = tasks sharing everything possible

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 */
}
```



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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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    ... /* 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.

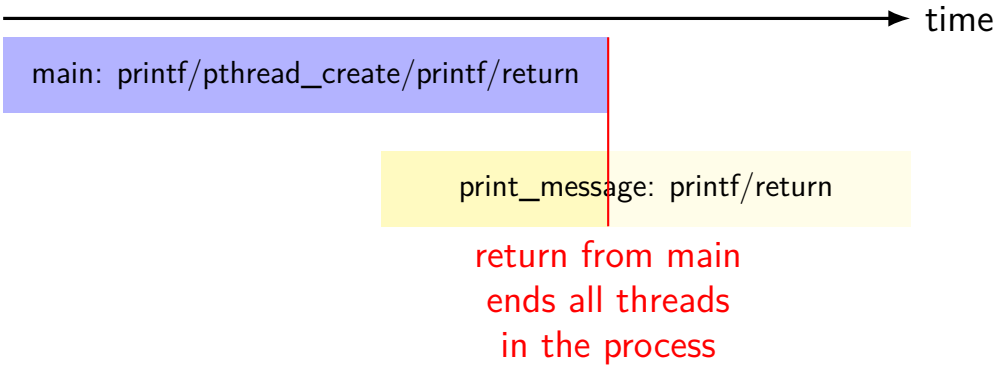
What happened?

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, returns 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];
}
```

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

values, results: global variables — shared

sum example (only globals)

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int results[2];
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    for (int i = 0; i < 512; ++i)
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    results[0] = sum;
    return NULL;
}
void *sum_back(void *ignored_argument) {
    int sum = 0;
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    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];
}
```

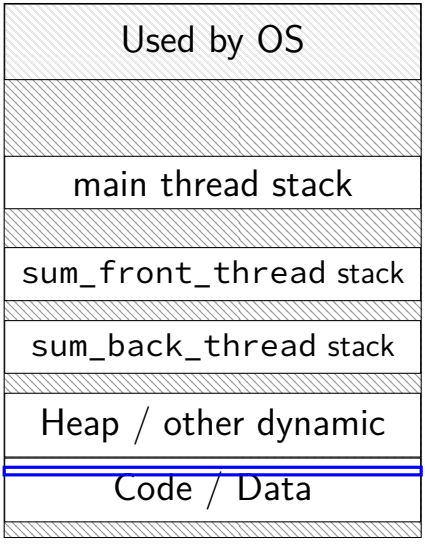
two different functions
happen to be the same except for some numbers

sum example (only globals)

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 value
int resul
void *sum
    int s
    for (
        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



0xFFFF FFFF FFFF FFFF

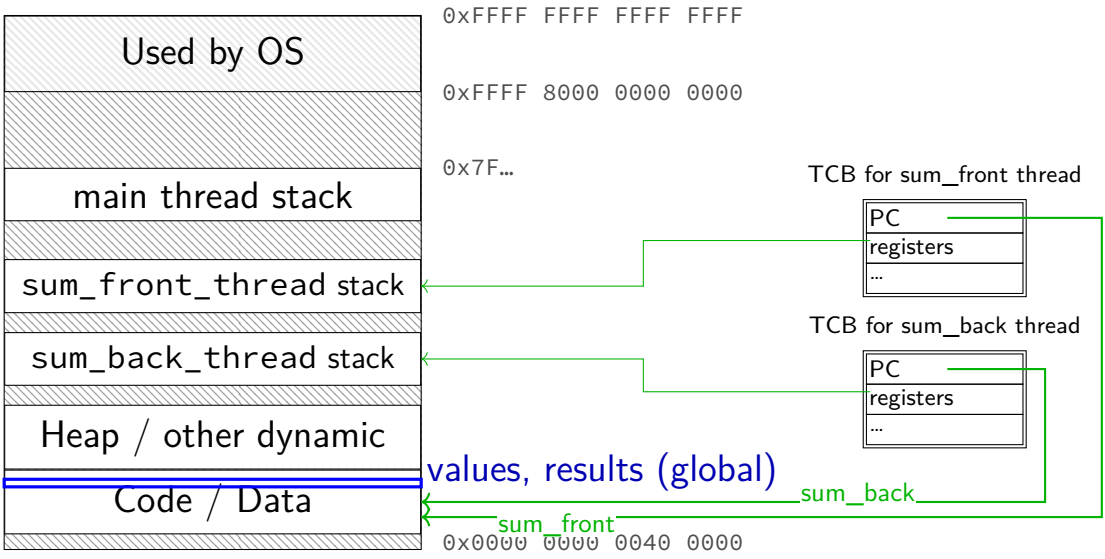
0xFFFF 8000 0000 0000

0x7F…

values, results (global)

0x0000 0000 0040 0000

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];
}
```

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    results[id] = sum;
    return NULL;
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    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)

values: global variable — shared

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    int sum = 0;
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        sum += values[i];
    }
    my_info->result = sum;
    return NULL;
}
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    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]);
    }
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        sum += values[i];
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    }
    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!

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    }
    for (int i = 0; i < 2; ++i)
        pthread_join(threads[i], NULL);
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}
```
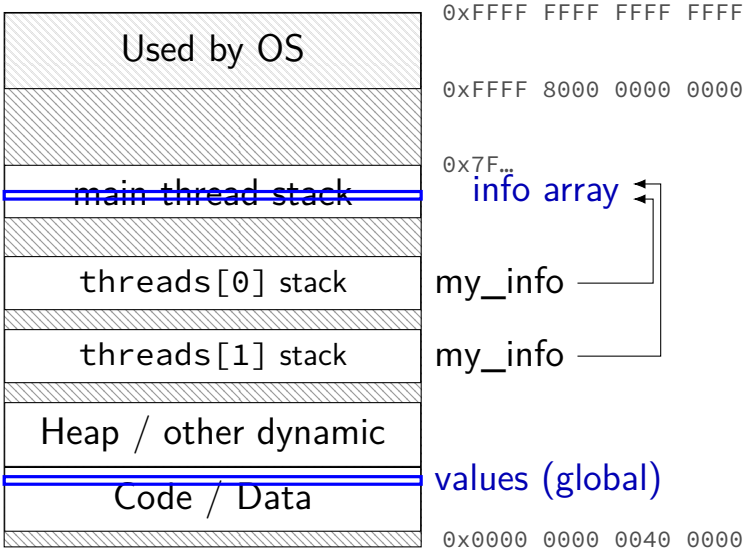

thread_sum memory layout (info struct)



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);
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    }
    my_info->result = sum;
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    }
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        sum += my_info->values[i];
    }
    my_info->result = sum;
    return NULL;

}
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    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;
}
```
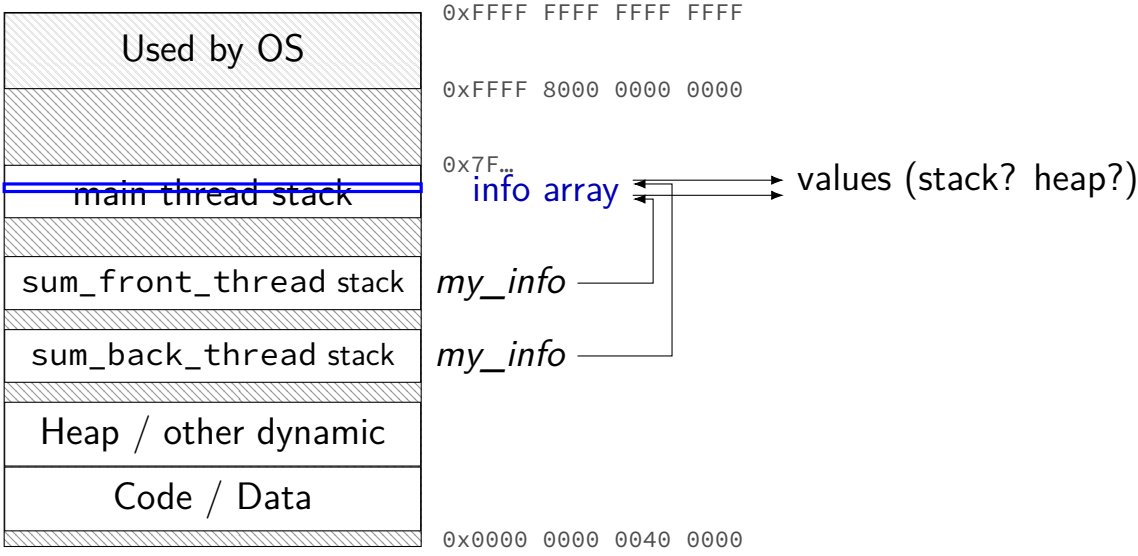

program memory (to main stack)



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;
}

void 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) {
    ...
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    }
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    }
    return info;
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    delete[] info;
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}
```
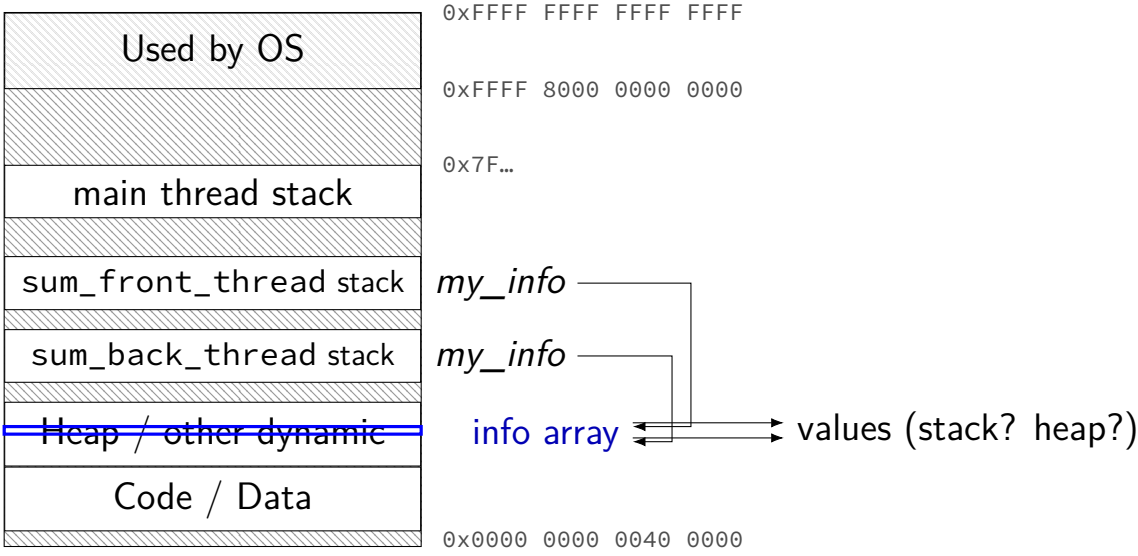
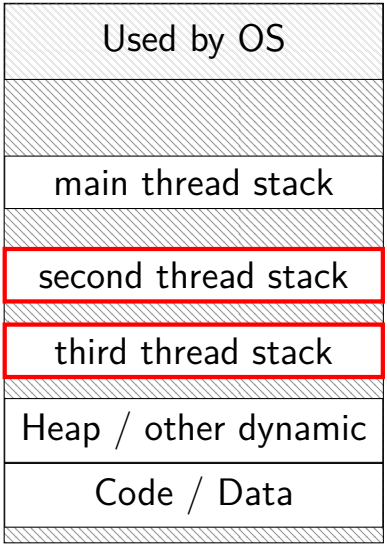

thread_sum memory (heap version)



what's wrong with this?

```
/* omitted: headers, using statements */
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, &string_ptr);
  cout << "string is " << *string_ptr;
}
```

program memory



0xFFFF FFFF FFFF FFFF

0xFFFF 8000 0000 0000

0x7F…

dynamically allocated stacks

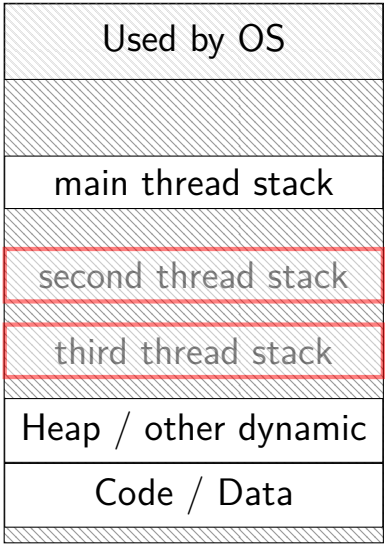
`string result` allocated here

`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 */
}
```

the correctness problem

schedulers introduce non-determinism

- scheduler might run threads in any order
- scheduler can switch threads at any time

worse with threads on multiple cores

- cores not precisely synchronized (stalling for caches, etc., etc.)
- different cores happen in different order each time

allows for "race condition" bugs

- outcome depends on whether one thread can 'race' ahead of another

...to be avoided by synchronization constructs

- what we'll talk about for a while...

example application: ATM server

commands: withdraw, deposit

one correctness goal: don't lose money

ATM server
(pseudocode)

```
ServerLoop() {
    while (true) {
        ReceiveRequest(&operation, &accountNumber, &amount);
        if (operation == DEPOSIT) {
            Deposit(accountNumber, amount);
        } else ...
    }
}
Deposit(accountNumber, amount) {
    account = GetAccount(accountId);
    account->balance += amount;
    SaveAccountUpdates(account);
}
```

a threaded server?

```
Deposit(accountNumber, amount) {
    account = GetAccount(accountId);
    account->balance += amount;
    SaveAccountUpdates(account);
}
```

maybe GetAccount/SaveAccountUpdates can be slow?

- read/write disk sometimes? contact another server sometimes?

maybe lots of requests to process?

- maybe real logic has more checks than Deposit()
- ...

all reasons to handle multiple requests at once

→ many threads all running the server loop

multiple threads

```
main() {
    for (int i = 0; i < NumberOfThreads; ++i) {
        pthread_create(&server_loop_threads[i], NULL,
                       ServerLoop, NULL);
    }
    ...
}

ServerLoop() {
    while (true) {
        ReceiveRequest(&operation, &accountNumber, &amount);
        if (operation == DEPOSIT) {
            Deposit(accountNumber, amount);
        } else ...
    }
}
```

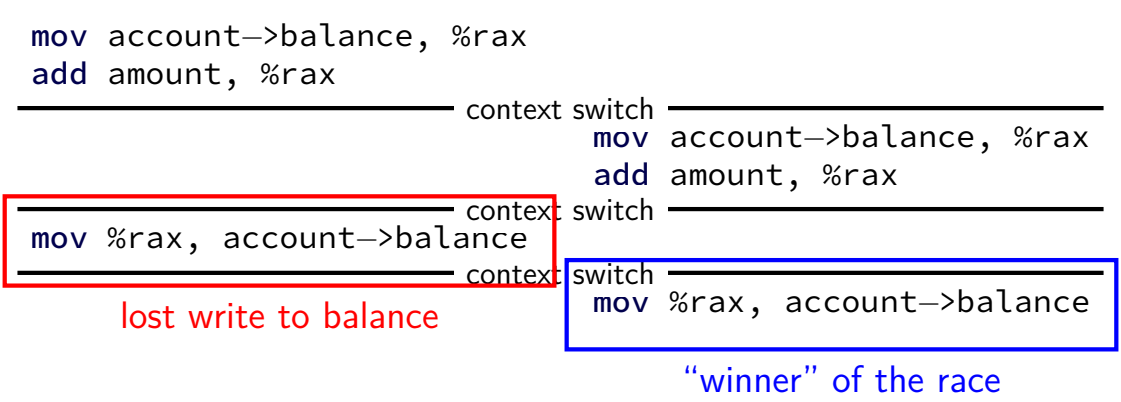
the lost write

`account->balance += amount;` (in two threads, same account)

Thread A		Thread B
`mov account->balance, %rax`		
`add amount, %rax`		
	context switch	
		`mov account->balance, %rax`
		`add amount, %rax`
	context switch	
`mov %rax, account->balance`		
	context switch	
		`mov %rax, account->balance`

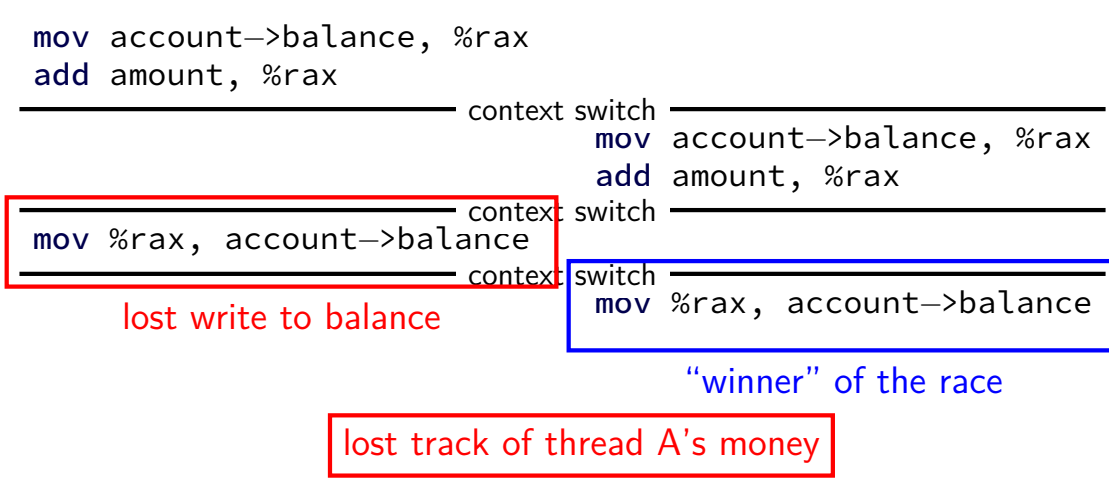
the lost write

`account->balance += amount;` (in two threads, same account)



the lost write

`account->balance += amount;` (in two threads, same account)



thinking about race conditions (1)

what are the possible values of x?

(initially $x = y = 0$)

Thread A	**Thread B**
$x \leftarrow 1$	$y \leftarrow 2$

thinking about race conditions (1)

what are the possible values of x?

(initially $x = y = 0$)

Thread A	**Thread B**
$x \leftarrow 1$	$y \leftarrow 2$

must be 1. Thread B can't do anything

thinking about race conditions (2)

what are some possible values of x?

(initially $x = y = 0$)

Thread A	**Thread B**
$x \leftarrow y + 1$	$y \leftarrow 2$
	$y \leftarrow y \times 2$

thinking about race conditions (2)

what are some possible values of x?

(initially $x = y = 0$)

Thread A	**Thread B**
$x \leftarrow y + 1$	$y \leftarrow 2$
	$y \leftarrow y \times 2$

if A goes first, then B: 1

if B goes first, then A: 5

if B line one, then A, then B line two: 3

thinking about race conditions (3)

what are the possible values of x?

(initially $x = y = 0$)

Thread A	**Thread B**
$x \leftarrow 1$	$x \leftarrow 2$

thinking about race conditions (3)

what are the possible values of x?

(initially $x = y = 0$)

Thread A	**Thread B**
$x \leftarrow 1$	$x \leftarrow 2$

1 or 2

thinking about race conditions (3)

what are the possible values of x?

(initially $x = y = 0$)

Thread A	**Thread B**
$x \leftarrow 1$	$x \leftarrow 2$

1 or 2

...but why not 3?

B: x bit 0 $\leftarrow 0$
A: x bit 0 $\leftarrow 1$
A: x bit 1 $\leftarrow 0$
B: x bit 1 $\leftarrow 1$

thinking about race conditions (2)

what are some possible values of x?

(initially $x = y = 0$)

Thread A	Thread B
$x \leftarrow y + 1$	$y \leftarrow 2$
	$y \leftarrow y \times 2$

if A goes first, then B: 1

if B goes first, then A: 5

if B line one, then A, then B line two: 3

...and why not 7:

B (start): $y \leftarrow 2 = 0010_{\text{TWO}}$; then y bit 3 $\leftarrow$ 0; y bit 2 $\leftarrow$ 1; then
A: x $\leftarrow 110_{\text{TWO}} + 1 = 7$; then
B (finish): y bit 1 $\leftarrow$ 0; y bit 0 $\leftarrow$ 0

atomic operation

atomic operation = operation that runs to completion or not at all

we will use these to let threads work together

most machines: loading/storing (aligned) words is atomic

- so can't get 3 from $x \leftarrow 1$ and $x \leftarrow 2$ running in parallel
- aligned ≈ address of word is multiple of word size (typically done by compilers)

but some instructions are not atomic; examples:

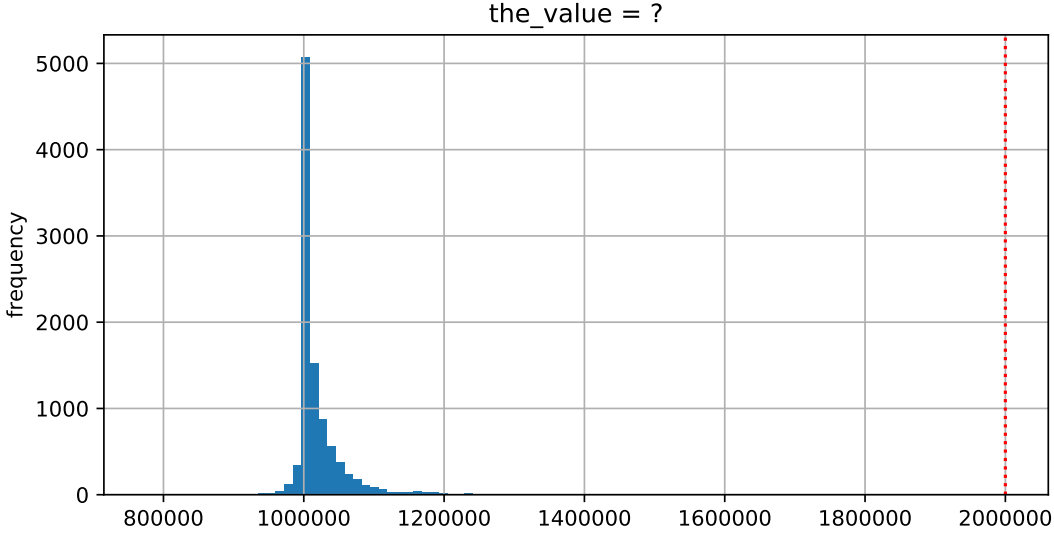
- x86: integer add constant to memory location
- many CPUs: loading/storing values that cross cache blocks
  - e.g. if cache blocks `0x40` bytes, load/store 4 byte from addr. `0x3E` is not atomic

lost adds (program)

```
.global update_loop
update_loop:
    addl $1, the_value // the_value (global variable) += 1
    dec %rdi           // argument 1 -= 1
    jg update_loop     // if argument 1 >= 0 repeat
    ret
```

```
int the_value;
extern void *update_loop(void *);
int main(void) {
    the_value = 0;
    pthread_t A, B;
    pthread_create(&A, NULL, update_loop, (void*) 1000000);
    pthread_create(&B, NULL, update_loop, (void*) 1000000);
    pthread_join(A, NULL);
    pthread_join(B, NULL);
    // expected result: 1000000 + 1000000 = 2000000
    printf("the_value = %d\n", the_value);
}
```

lost adds (results)



but how?

probably not possible on single core

- exceptions can't occur in the middle of `add` instruction

...but 'add to memory' implemented with multiple steps

- still needs to load, add, store internally
- can be interleaved with what other cores do

but how?

probably not possible on single core

- exceptions can't occur in the middle of `add` instruction

...but 'add to memory' implemented with multiple steps

- still needs to load, add, store internally
- can be interleaved with what other cores do

(and actually it's more complicated than that — we'll talk later)

so, what is actually atomic

for now we'll assume: load/stores of 'words'
(64-bit machine = 64-bits words)

in general: processor designer will tell you

their job to design caches, etc. to work as documented

too much milk

roommates Alice and Bob want to keep fridge stocked with milk:

time	Alice	Bob
3:00	look in fridge. no milk	
3:05	leave for store	
3:10	arrive at store	look in fridge. no milk
3:15	buy milk	leave for store
3:20	return home, put milk in fridge	arrive at store
3:25		buy milk
3:30		return home, put milk in fridge

how can Alice and Bob coordinate better?

too much milk "solution" 1 (algorithm)

leave a note: "I am buying milk"

- place before buying
- remove after buying
- don't try buying if there's a note

≈ setting/checking a variable (e.g. "`note = 1`")

- with atomic load/store of variable

```
if (no milk) {
    if (no note) {
        leave note;
        buy milk;
        remove note;
    }
}
```

too much milk “solution” 1 (timeline)

Alice

```
if (no milk) {
    if (no note) {

        leave note;
        buy milk;
        remove note;
    }
}
```

Bob

```
if (no milk) {
    if (no note) {

        leave note;
        buy milk;
        remove note;
    }
}
```

too much milk "solution" 2 (algorithm)

intuition: leave note when buying or checking if need to buy

```
leave note;
if (no milk) {
    if (no note) {
        buy milk;
    }
}
remove note;
```

too much milk: “solution” 2 (timeline)

Alice

```
leave note;
if (no milk) {
    if (no note) {
        buy milk;
    }
}
remove note;
```

too much milk: “solution” 2 (timeline)

Alice

```
leave note;
if (no milk) {
    if (no note) {
        buy milk;
    }
}
remove note;
```

← but there's always a note

too much milk: “solution” 2 (timeline)

Alice

```
leave note;
if (no milk) {
    if (no note) {
        buy milk;
    }
}
remove note;
```

← but there's always a note

…will never buy milk (twice *or* once)

“solution” 3: algorithm

intuition: label notes so Alice knows which is hers (and vice-versa)

computer equivalent: separate noteFromAlice and noteFromBob variables

Alice

```
leave note from Alice;
if (no milk) {
    if (no note from Bob) {
        buy milk
    }
}
remove note from Alice;
```

Bob

```
leave note from Bob;
if (no milk) {
    if (no note from Alice)
        buy milk
    }
}
remove note from Bob;
```

too much milk: “solution” 3 (timeline)

Alice

```
leave note from Alice
if (no milk) {
    if (no note from Bob) {
        buy milk
    }
}
remove note from Alice
```

Bob

```
leave note from Bob
if (no milk) {
    if (no note from Alice) {
        buy milk
    }
}
remove note from Bob
```

too much milk: is it possible

is there a solutions with writing/reading notes?

$\approx$ loading/storing from shared memory

yes, but it's not very elegant

too much milk: solution 4 (algorithm)

Alice

```
leave note from Alice
while (note from Bob) {
    do nothing
}
if (no milk) {
    buy milk
}
remove note from Alice
```

Bob

```
leave note from Bob
if (no note from Alice) {
    if (no milk) {
        buy milk
    }
}
remove note from Bob
```

too much milk: solution 4 (algorithm)

Alice

```
leave note from Alice
while (note from Bob) {
    do nothing
}
if (no milk) {
    buy milk
}
remove note from Alice
```

Bob

```
leave note from Bob
if (no note from Alice) {
    if (no milk) {
        buy milk
    }
}
remove note from Bob
```

exercise (hard): prove (in)correctness

too much milk: solution 4 (algorithm)

Alice

```
leave note from Alice
while (note from Bob) {
    do nothing
}
if (no milk) {
    buy milk
}
remove note from Alice
```

Bob

```
leave note from Bob
if (no note from Alice) {
    if (no milk) {
        buy milk
    }
}
remove note from Bob
```

exercise (hard): prove (in)correctness

too much milk: solution 4 (algorithm)

Alice

```
leave note from Alice
while (note from Bob) {
    do nothing
}
if (no milk) {
    buy milk
}
remove note from Alice
```

Bob

```
leave note from Bob
if (no note from Alice) {
    if (no milk) {
        buy milk
    }
}
remove note from Bob
```

exercise (hard): prove (in)correctness

exercise (hard): extend to three people

Peterson's algorithm

general version of solution

see, e.g., Wikipedia

we'll use special hardware support instead

some definitions

mutual exclusion: ensuring only one thread does a particular thing at a time

- like checking for and, if needed, buying milk

some definitions

mutual exclusion: ensuring only one thread does a particular thing at a time

- like checking for and, if needed, buying milk

critical section: code that exactly one thread can execute at a time

- result of critical section

some definitions

mutual exclusion: ensuring only one thread does a particular thing at a time

> like checking for and, if needed, buying milk

critical section: code that exactly one thread can execute at a time

> result of critical section

lock: object only one thread can hold at a time

> interface for creating critical sections

the lock primitive

locks: an object with (at least) two operations:

- *acquire* or *lock* — wait until lock is free, then "grab" it
- *release* or *unlock* — let others use lock, wakeup waiters

typical usage: everyone acquires lock before using shared resource

- forget to acquire lock? weird things happen

```
Lock(MilkLock);
if (no milk) {
    buy milk
}
Unlock(MilkLock);
```

pthread mutex

```
#include <pthread.h>

pthread_mutex_t MilkLock;
pthread_mutex_init(&MilkLock, NULL);
...
pthread_mutex_lock(&MilkLock);
if (no milk) {
    buy milk
}
pthread_mutex_unlock(&MilkLock);
```

xv6 spinlocks

```
#include "spinlock.h"
...
struct spinlock MilkLock;
initlock(&MilkLock, "name for debugging");
...
acquire(&MilkLock);
if (no milk) {
    buy milk
}
release(&MilkLock);
```

backup slides

lottery scheduler assignment

track "ticks" process runs

- = number of times scheduled
- simplification: don't care if process uses less than timeslice

new system call: getprocesesinfo

- copy info from process table into user space

new system call: settickets

- set number of tickets for current process
- should be inherited by fork

scheduler: choose pseudorandom weighted by tickets

- caution! no floating point

passing thread IDs (1)

```
DataType items[1000];
void *thread_function(void *argument) {
    int thread_id = (int) argument;
    int start = 500 * thread_id;
    int end = start + 500;
    for (int i = start; i < end; ++i) {
        DoSomethingWith(items[i]);
    }
    ...
}
void run_threads() {
    vector<pthread_t> threads(2);
    for (int i = 0; i < 2; ++i) {
        pthread_create(&threads[i], NULL,
            thread_function, (void*) i);
    }
}
```

passing thread IDs (1)

```
DataType items[1000];
void *thread_function(void *argument) {
    int thread_id = (int) argument;
    int start = 500 * thread_id;
    int end = start + 500;
    for (int i = start; i < end; ++i) {
        DoSomethingWith(items[i]);
    }
    ...
}
void run_threads() {
    vector<pthread_t> threads(2);
    for (int i = 0; i < 2; ++i) {
        pthread_create(&threads[i], NULL,
            thread_function, (void*) i);
    }
}
```

passing thread IDs (2)

```
DataType items[1000];
int num_threads;
void *thread_function(void *argument) {
    int thread_id = (int) argument;
    int start = thread_id * (1000 / num_threads);
    int end = start + (1000 / num_threads);
    if (thread_id == num_threads - 1) end = 1000;
    for (int i = start; i < end; ++i) {
        DoSomethingWith(items[i]);
    }
    ...
}
void run_threads() {
    vector<pthread_t> threads(num_threads);
    for (int i = 0; i < num_threads; ++i) {
        pthread_create(&threads[i], NULL,
            thread_function, (void*) i);
    }
    ...
}
```

passing thread IDs (2)

```
DataType items[1000];
int num_threads;
void *thread_function(void *argument) {
    int thread_id = (int) argument;
    int start = thread_id * (1000 / num_threads);
    int end = start + (1000 / num_threads);
    if (thread_id == num_threads - 1) end = 1000;
    for (int i = start; i < end; ++i) {
        DoSomethingWith(items[i]);
    }
    ...
}
void run_threads() {
    vector<pthread_t> threads(num_threads);
    for (int i = 0; i < num_threads; ++i) {
        pthread_create(&threads[i], NULL,
            thread_function, (void*) i);
    }
    ...
}
```

passing data structures

```
class ThreadInfo {
public:
    ...
};

void *thread_function(void *argument) {
    ThreadInfo *info = (ThreadInfo *) argument;
    ...
    delete info;
    return NULL;
}

void run_threads(int N) {
    vector<pthread_t> threads(num_threads);
    for (int i = 0; i < num_threads; ++i) {
        pthread_create(&threads[i], NULL,
            thread_function, (void *) new ThreadInfo(...));
    }
    ...
}
```

passing data structures

```
class ThreadInfo {
public:
    ...
};

void *thread_function(void *argument) {
    ThreadInfo *info = (ThreadInfo *) argument;
    ...
    delete info;
    return NULL;
}

void run_threads(int N) {
    vector<pthread_t> threads(num_threads);
    for (int i = 0; i < num_threads; ++i) {
        pthread_create(&threads[i], NULL,
            thread_function, (void *) new ThreadInfo(...));
    }
    ...
}
```