# threads 1

# Changelog

8 March 2021: sum example (only globals): correct `pthread_join(&sum_front_thread, NULL)` to `pthread_join(sum_fron_thread, NULL)` (and same for back)

# last time (1)

shortest remaining time first

- minimize mean turnaround time
- order by *time left in current CPU burst*

multi-level feedback queues

- thread priority ≈ thread CPU burst time
- update priority based on actual time used
  - too much time? lower priority
  - too little time? higher priority
- priority level determines maximum time allowed

# last time (2)

Linux's Completely Fair Scheduler

- track *virtual time* based on used CPU time
- program with lowest virtual time runs first
- limit how much time programs that sleep can 'bank'

how CFS divides up CPU if equal weights

- long-term evenly divided among runnable programs
- if one program "gets ahead" of another, it will have more virtual time → lower priority
- if program can't use all its time, remainder divided among other programs

# CFS time splitting

each thread gets equal share of CPU

what if one thread can't use that full share?

- that thread's share divided among remaining threads

caveat: if thread can't start I/O as soon as it would otherwise, might be sleeping for longer than it would running alone

caveat: limit on 'banked' virtual time can affect this

# aside on CFS exercises

possibility of delaying I/O operation starting makes them more complicated than I wanted

# anonymous feedback

yes, we keep old assignment submissions

not graded unless some issue with deadlines/uploading errors/etc. comes up

# 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

(not covered this semester) real-world deadlines: earliest deadline first or similar

favoring certain users: strict priority

# 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

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- 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

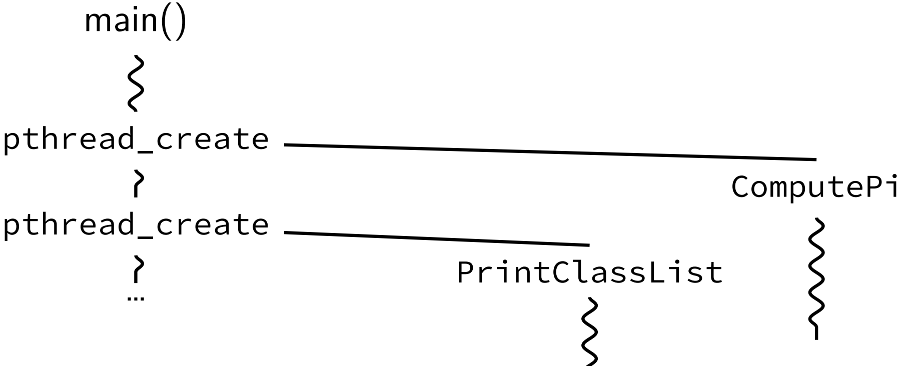
- `clone(0, ...)` — similar to `fork()`
- `clone(CLONE_FILES, ...)` — like fork(), but **sharing** open files
- `clone(CLONE_VM, new_stack_pointer, ...)` — like fork(), but **sharing** address space

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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    ... /* 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

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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.

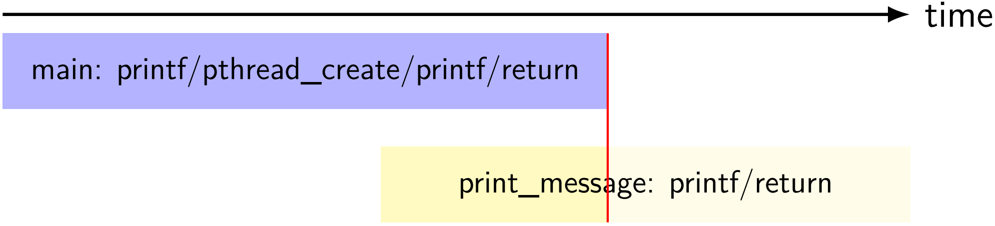
What happened?

# 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?


time
main: printf/pthread_create/printf/return
print_message: printf/return

return from main
ends all threads
in the process

# 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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int values[1024];
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void *sum_front(void *ignored_
    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];
}
```

values, results: global variables — shared

# sum example (only globals)

two different functions

happen to be the same except for some numbers

```
int values[1024];
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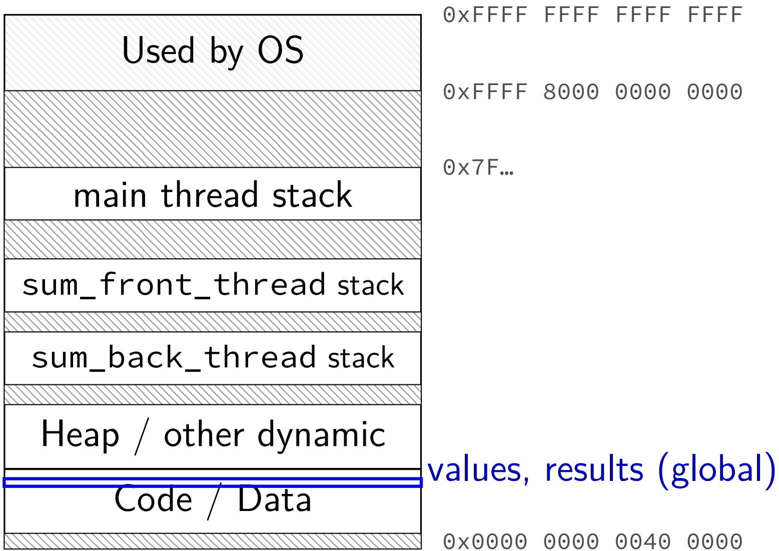
void *sum_front(void *
    int sum = 0;
    for (int i = 0; i < 512; ++i)
        sum += values[i];
    results[0] = sum;
    return NULL;
}
void *sum_back(void *ignored_argument) {
    int sum = 0;
    for (int i = 512; i < 1024; ++i)
        sum += values[i];
    results[1] = sum;
    return NULL;
}
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 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



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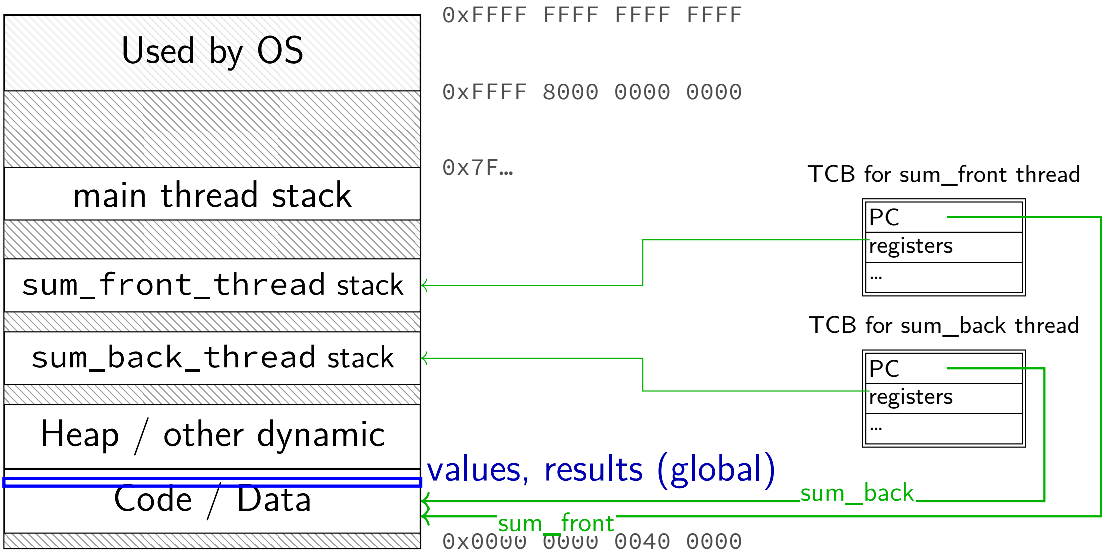

# sum example (to global, with thread IDs)

```
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;
}
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)

values: global variable — shared

```
int values[1024];
struct ThreadInfo
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    int sum = 0;
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        sum += values[i];
    }
    my_info->result = sum;
    return NULL;
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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)
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```

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    }
    my_info->result = sum;
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        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!

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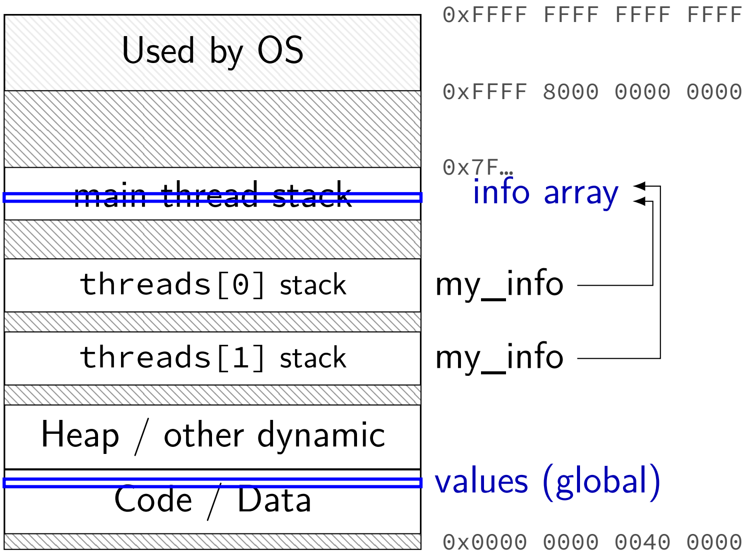
        pthread_create(&threads[i], NULL, sum_thread, &info[i]);
    }
    for (int i = 0; i < 2; ++i)
        pthread_join(threads[i], NULL);
    return info[0].result + info[1].result;
}
```

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

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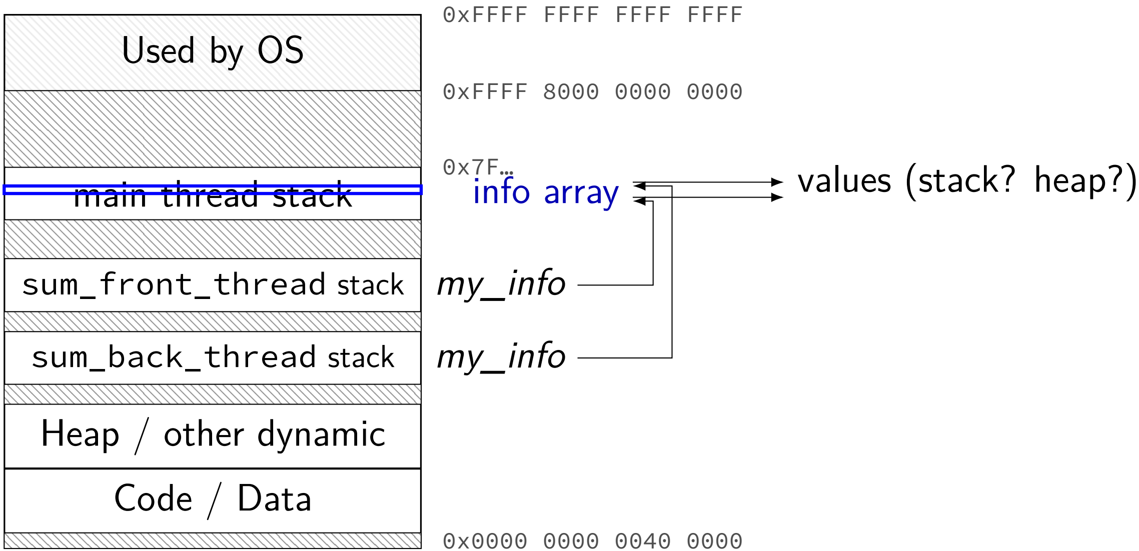
    for (int i = 0; i < 2; ++i) {
        info[i].values = values; info[i].start = i*512; info[i].end = (i+1)*512;
        pthread_create(&threads[i], NULL, sum_thread, (void *) &info[i]);
    }
    for (int i = 0; i < 2; ++i)
        pthread_join(threads[i], NULL);
    return info[0].result + info[1].result;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

# 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)

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    ...
}

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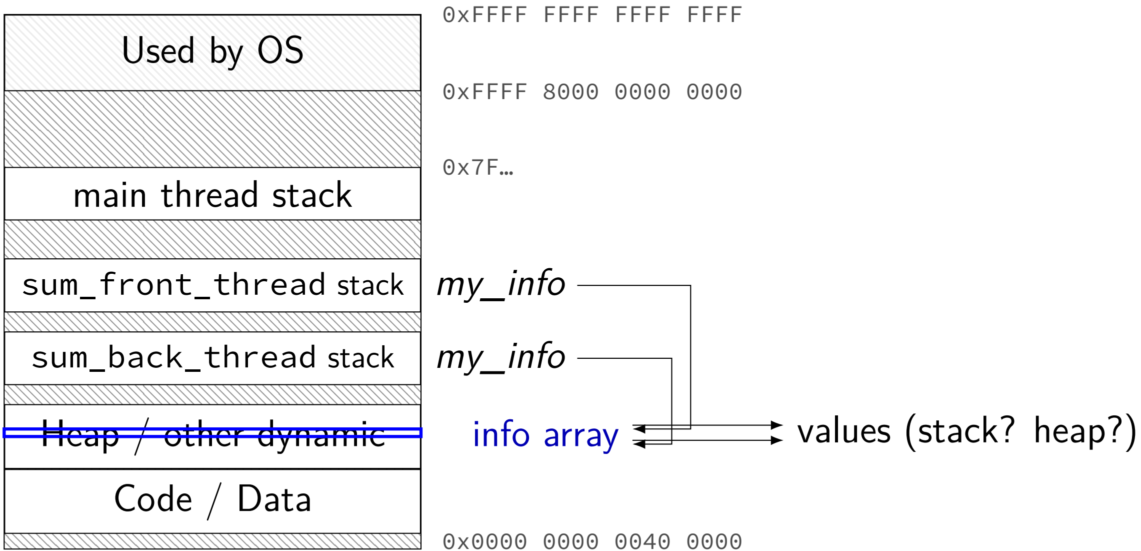
        pthread_join(info[i].thread, NULL);
    int result = info[0].result + info[1].result;
    delete[] info;
    return result;
}
```

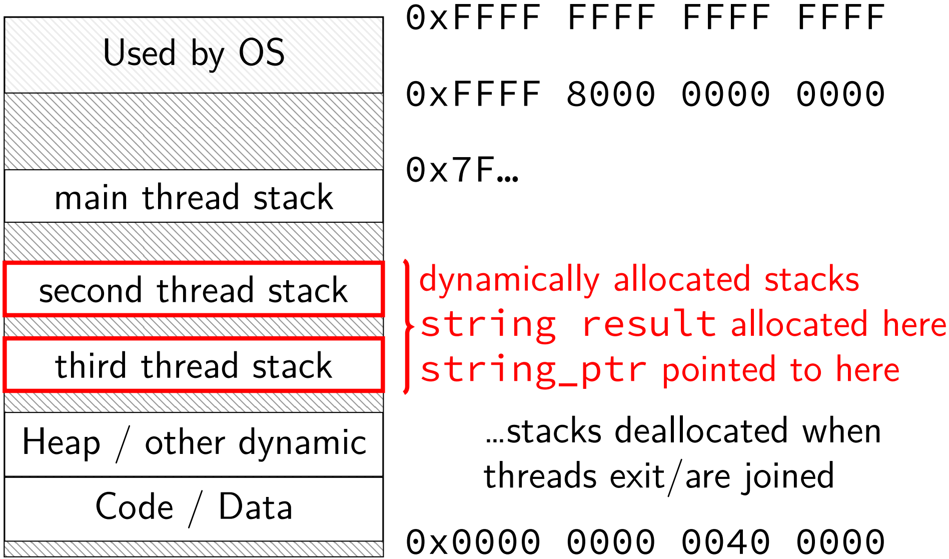
# thread_sum memory (heap version)



# 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



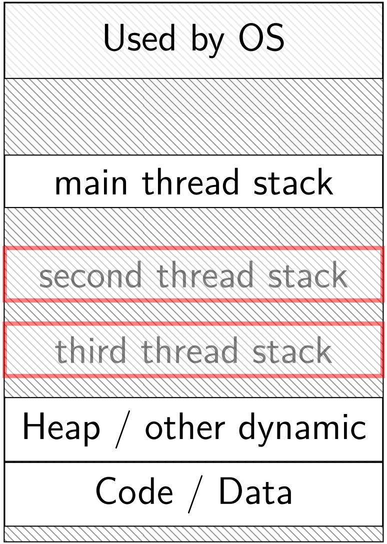
dynamically allocated stacks

`string result` allocated here

`string_ptr` pointed to here

…stacks deallocated when threads exit/are joined

# 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

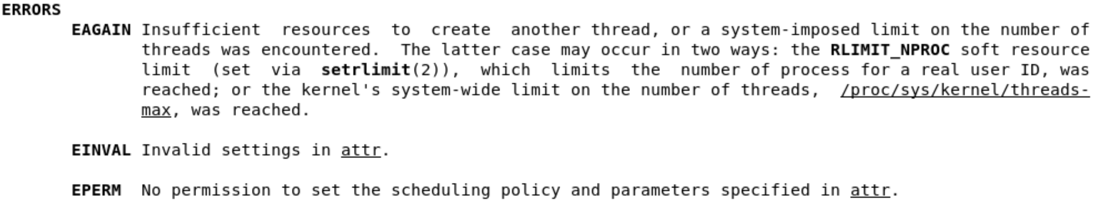
```
void *show_progress(void * ...) { ... }
void spawn_show_progress_thread() {
    pthread_t show_progress_thread;
    pthread_attr_t attrs;
    pthread_attr_init(&attrs);
    pthread_attr_setdetachstate(&attrs, PTHREAD_CREATE_DETACHED);
    pthread_create(&show_progress_thread, attrs,
            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

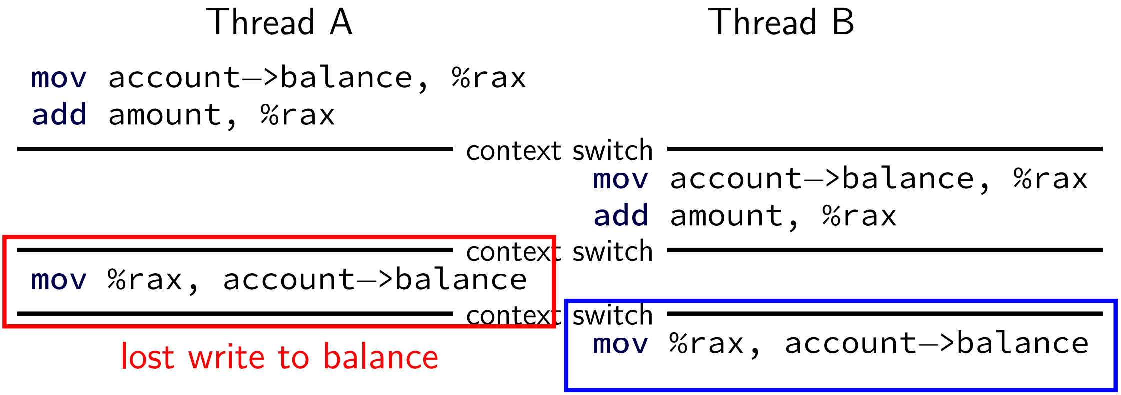
`account->balance += amount;` (in two threads, same account)

```
            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)



```
            Thread A                              Thread B

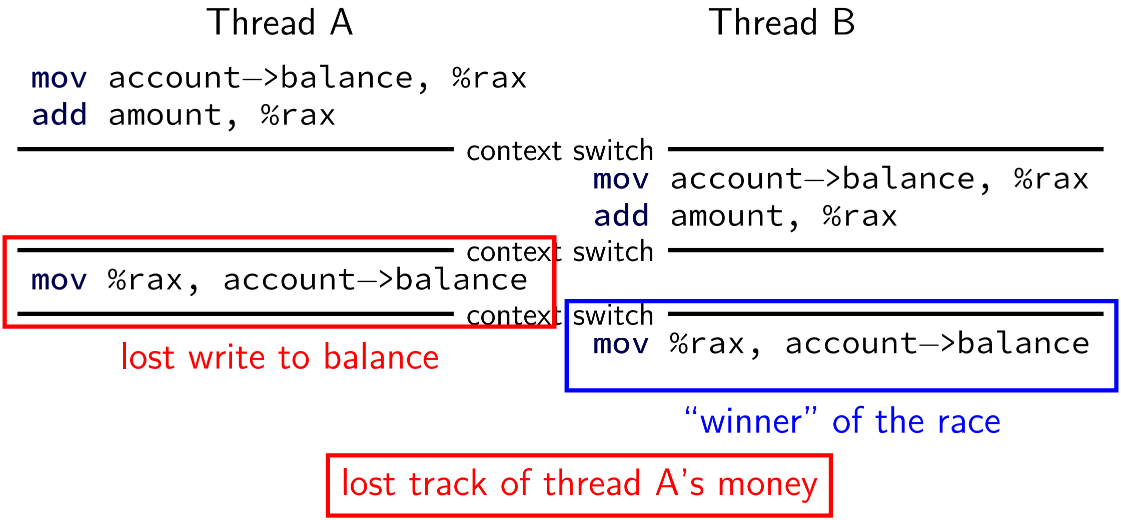
mov account->balance, %rax
add amount, %rax
──────────────────────── context switch ────────────────────────
                                      mov account->balance, %rax
                                      add amount, %rax
──────────────────────── context switch ────────────────────────
mov %rax, account->balance
──────────────────────── context switch ────────────────────────
                                      mov %rax, account->balance
```

lost write to balance

“winner” of the race

# 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
```

lost write to balance

“winner” of the race

lost track of thread A’s money

# backup slides

# other CFS parts

dealing with multiple CPUs

handling groups of related tasks

special ‘idle’ or ‘batch’ task settings

…

# CFS versus others

very similar to *stride scheduling*

- presented as a deterministic version of lottery scheduling
- Waldspurger and Weihl, “Stride Scheduling: Deterministic Proportional-Share Resource Management” (1995, same authors as lottery scheduling)

very similar to *weighted fair queuing*

- used to schedule network traffic
- Demers, Keshav, and Shenker, “Analysis and Simulation of a Fair Queuing Algorithm” (1989)