last time

C code and cache misses

handling writes

- Q1: add to cache on write? (write-allocate)
- Q2: update next level immediately? (write-back)

dirty bits for write-back

Side notes re caches

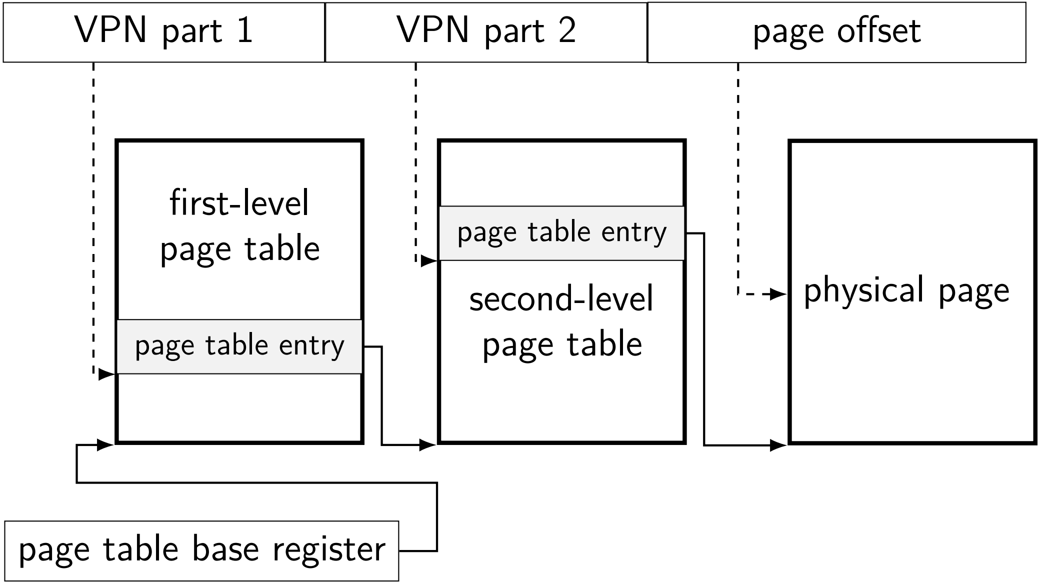
Multi-level caches

- First-level cache needs to be fast (and thus small) — 1-2 cycles hit time, so 32-64 KB L1 I/D
- But want high capacity!
- So today's high-end processors have two levels of cache per core, and then a huge last-level cache shared among the cores
- L2 and LLC are shared I/D; L2 is 256KB–1MB; L3 is usu. 128–512 MB
- Lots of extra hardware tricks to boost hit rate, e.g. prefetching

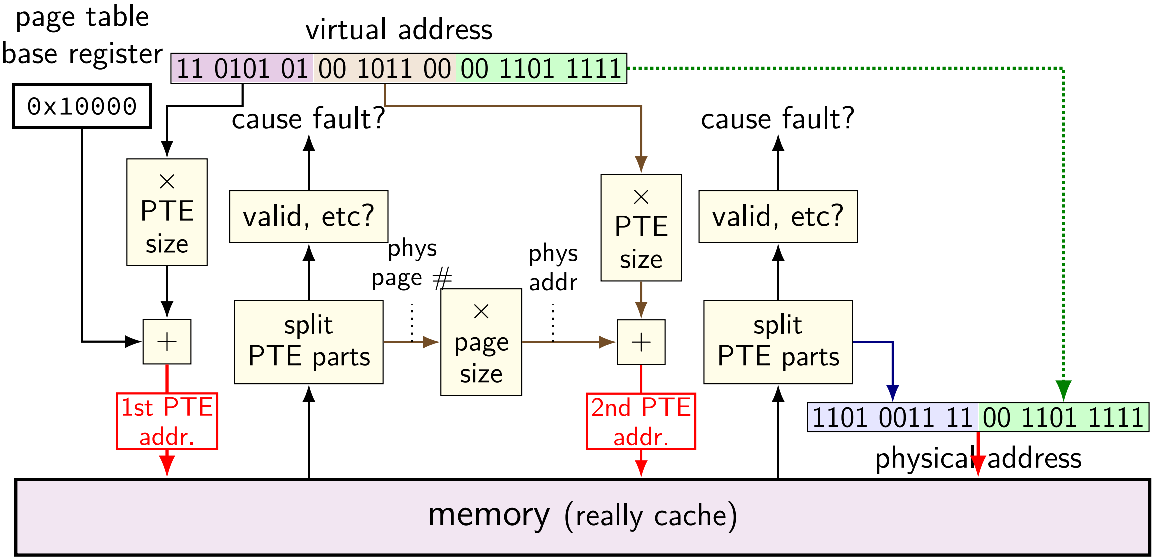
Cache lookups with virtual or physical address?

- Cache lookup with VA: aliasing among processes!
- But indexing using PA must wait for TLB (only an issue for L1)
- So index using VA bits (this means all index bits must be confined to page offset), and do TLB lookup in parallel
- Then tag check can use PA bits

another view



two-level page table lookup



cache accesses and multi-level PTs

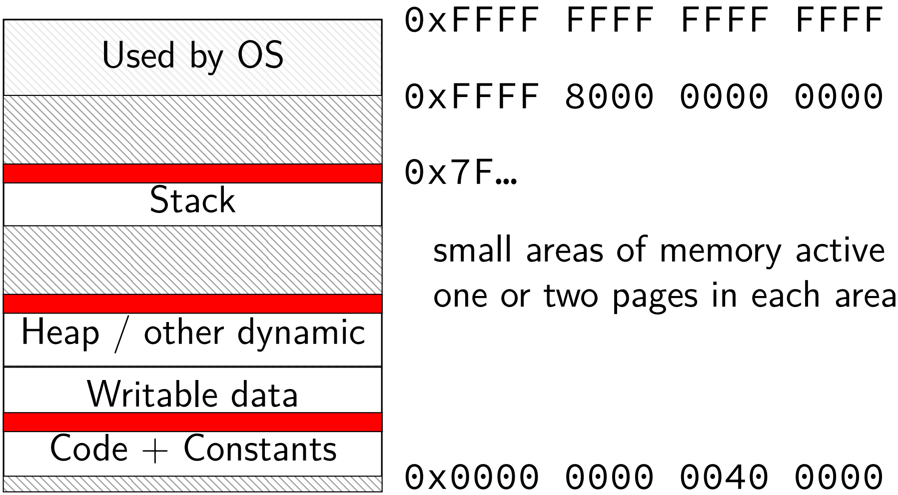
four-level page tables — five cache accesses per program memory access

L1 cache hits — typically a couple cycles each?

so add 8 cycles to each program memory access?

not acceptable

program memory active sets



small areas of memory active at a time

one or two pages in each area?

page table entries and locality

page table entries have excellent temporal locality

typically one or two pages of the stack active

typically one or two pages of code active

typically one or two pages of heap/globals active

each page contains whole functions, arrays, stack frames, etc.

page table entries and locality

page table entries have excellent temporal locality

typically one or two pages of the stack active

typically one or two pages of code active

typically one or two pages of heap/globals active

each page contains whole functions, arrays, stack frames, etc.

needed page table entries are very small

page table entry cache

caled a **TLB** (translation lookaside buffer)

(usually very small) cache of page table entries

L1 cache	TLB
physical addresses	virtual page numbers
bytes from memory	page table entries
tens of bytes per block	one page table entry per block
usually thousands of blocks	usually tens of entries

page table entry cache

caled a **TLB** (translation lookaside buffer)

(usually very small) cache of page table entries

L1 cache	TLB
physical addresses	virtual page numbers
bytes from memory	page table entries
tens of bytes per block	one page table entry per block
usually thousands of blocks	usually tens of entries

only caches the page table lookup itself
(generally) just entries from the last-level page tables

page table entry cache

caled a **TLB** (translation lookaside buffer)

(usually very small) cache of page table entries

L1 cache	TLB
physical addresses	virtual page numbers
bytes from memory	page table entries
tens of bytes per block	one page table entry per block
usually thousands of blocks	usually tens of entries

virtual page number divided into index + tag

page table entry cache

caled a **TLB** (translation lookaside buffer)

(usually very small) cache of page table entries

L1 cache	TLB
physical addresses	virtual page numbers
bytes from memory	page table entries
tens of bytes per block	one page table entry per block
usually thousands of blocks	usually tens of entries

not much spatial locality between page table entries
(they're used for kilobytes of data already)

page table entry cache

caled a **TLB** (translation lookaside buffer)

(usually very small) cache of page table entries

L1 cache	TLB
physical addresses	virtual page numbers
bytes from memory	page table entries
tens of bytes per block	one page table entry per block
usually thousands of blocks	usually tens of entries

0 block offset bits

page table entry cache

caled a **TLB** (translation lookaside buffer)

(usually very small) cache of page table entries

L1 cache	TLB
physical addresses	virtual page numbers
bytes from memory	page table entries
tens of bytes per block	one page table entry per block
usually thousands of blocks	usually tens of entries

few active page table entries at a time
enables highly associative cache designs

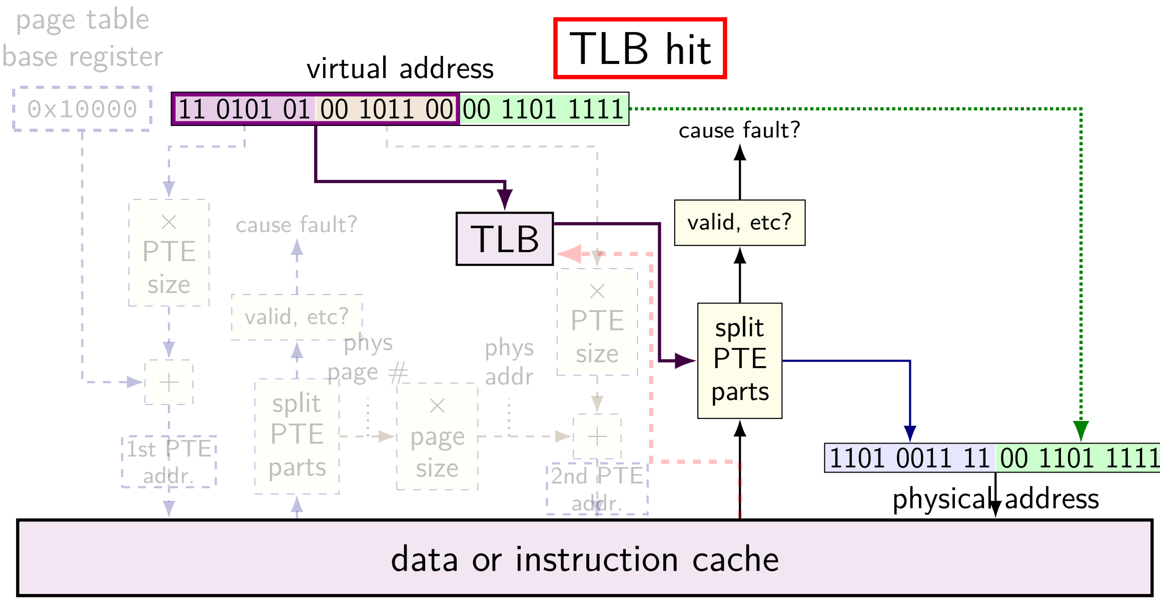
TLB and multi-level page tables

TLB caches valid last-level page table entries

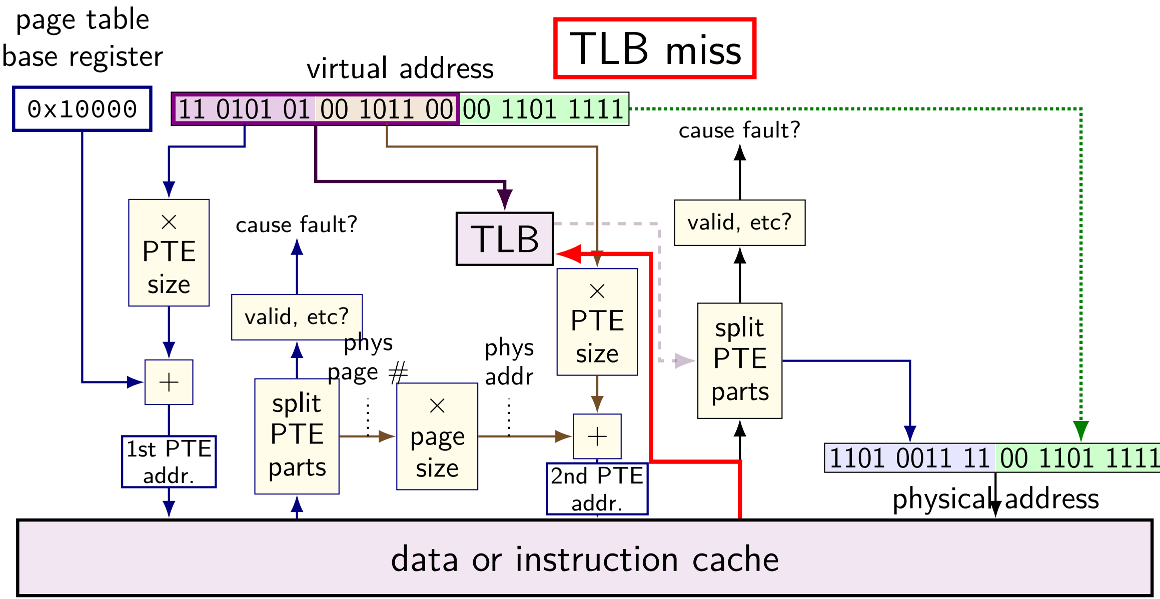
doesn't matter which last-level page table

means TLB output can be used directly to form address

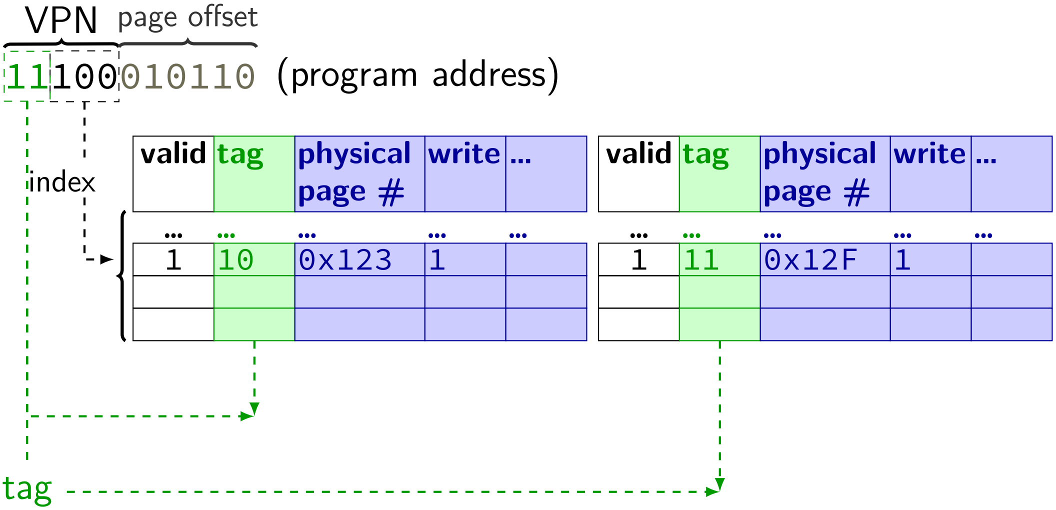
TLB and two-level lookup



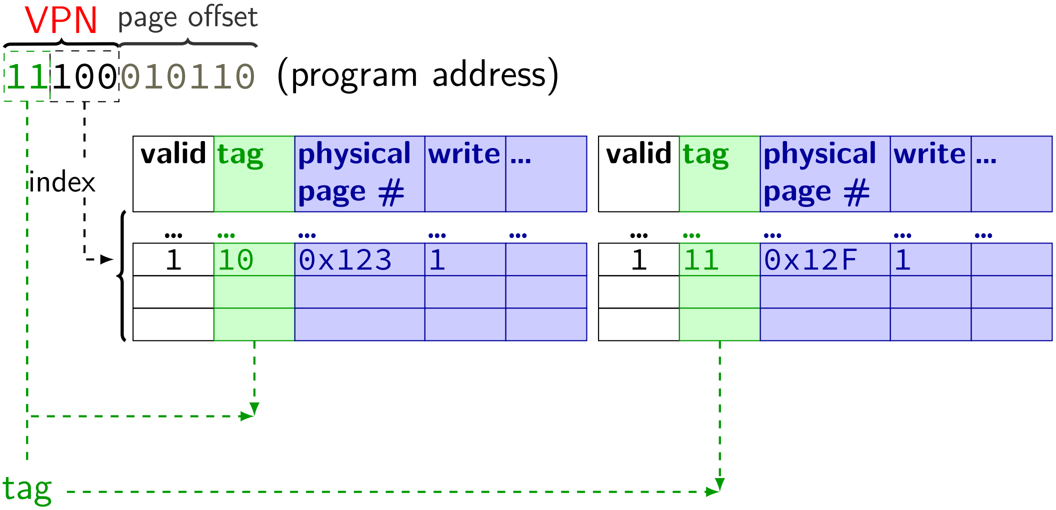
TLB and two-level lookup



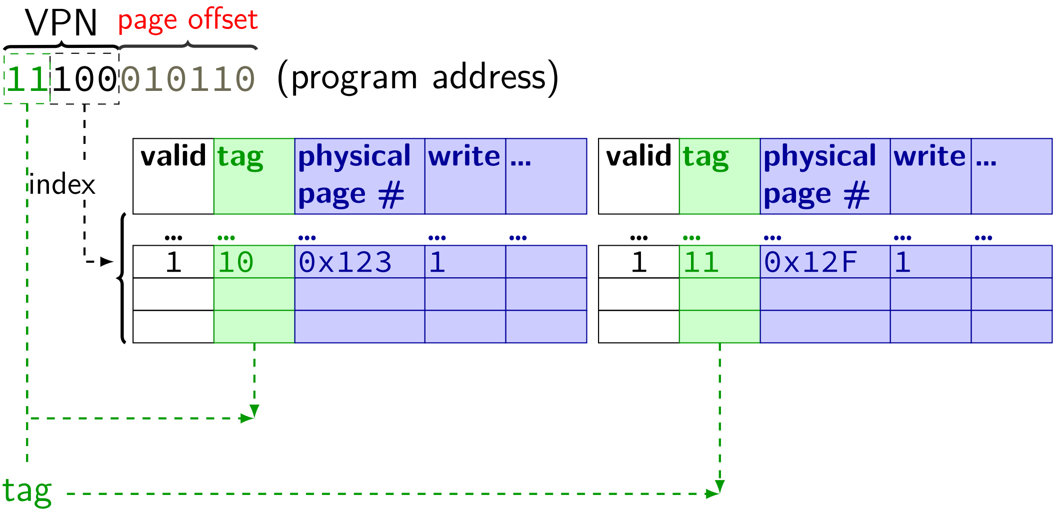
TLB organization (2-way set associative)



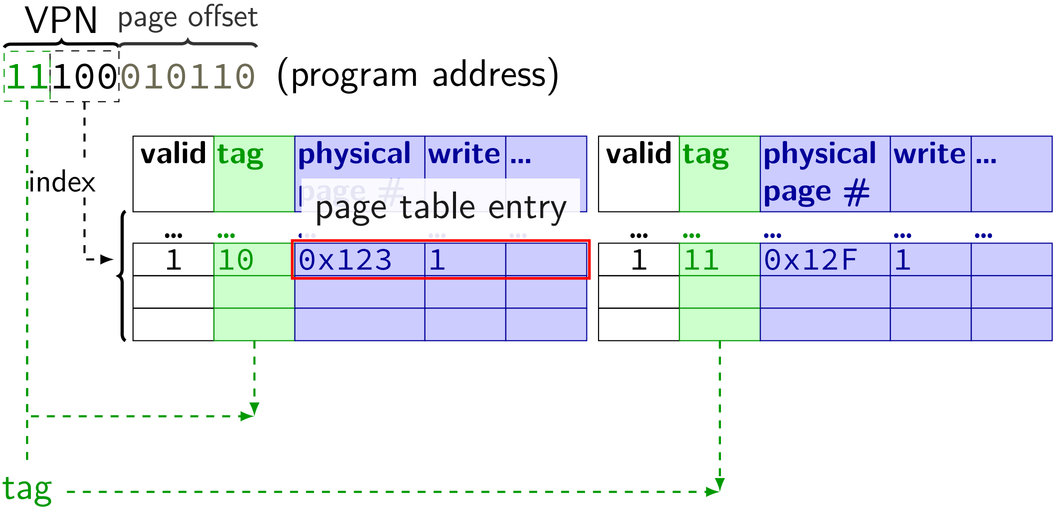
TLB organization (2-way set associative)



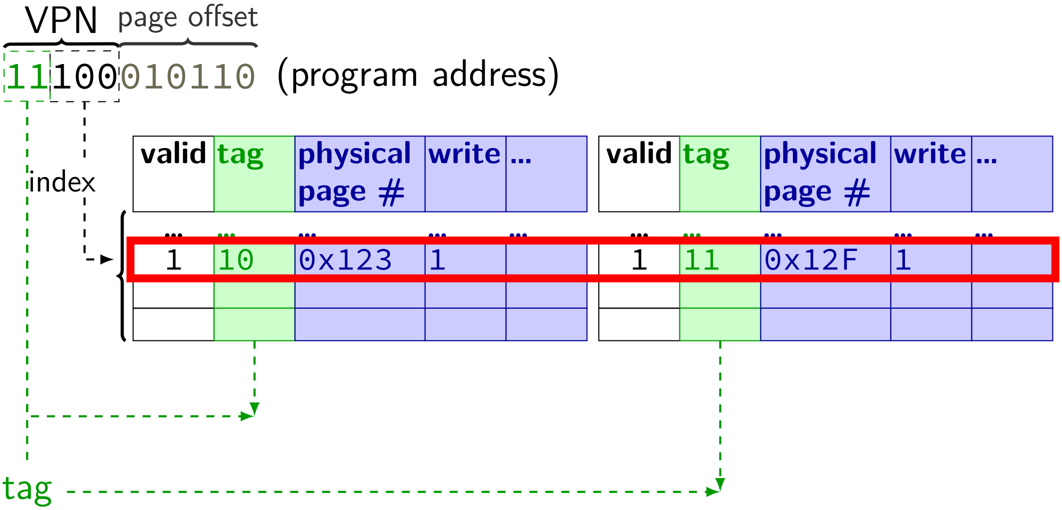
TLB organization (2-way set associative)



TLB organization (2-way set associative)



TLB organization (2-way set associative)



exercise: TLB access pattern (setup)

4-entry, 2-way TLB, LRU replacement policy, initially empty

4096 byte pages

how many index bits?

TLB index of virtual address 0x12345?

exercise: TLB access pattern

4-entry, 2-way TLB, LRU replacement policy, initially empty

4096 byte pages

type	virtual	physical
read	0x440030	0x554030
write	0x440034	0x554034
read	0x7FFFE008	0x556008
read	0x7FFFE000	0x556000
read	0x7FFFDFF8	0x5F8FF8
read	0x664080	0x5F9080
read	0x440038	0x554038
write	0x7FFFDFF0	0x5F8FF0

which are TLB hits? which are TLB misses? final contents of TLB?

why threads?

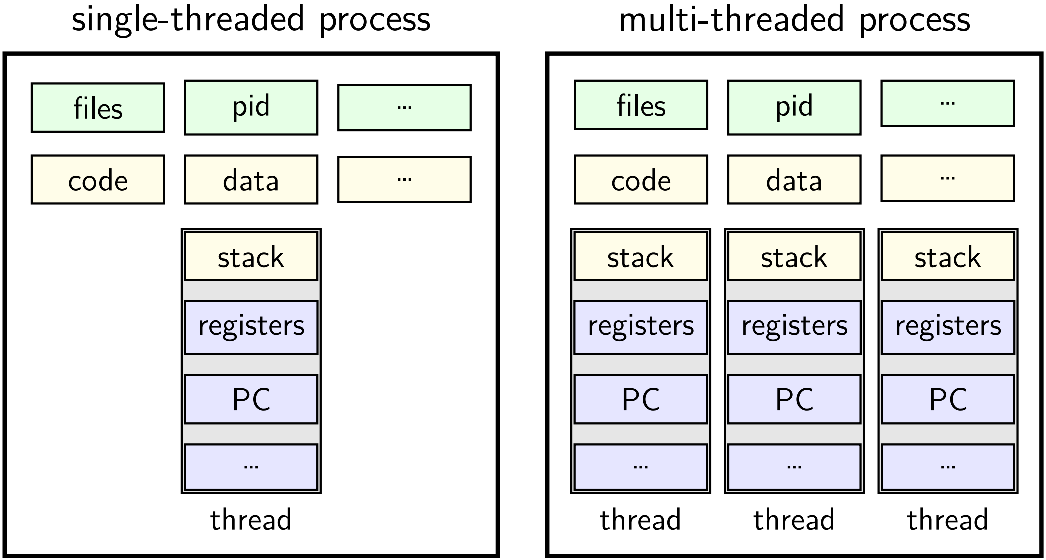
concurrency: different things happening at once

- 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

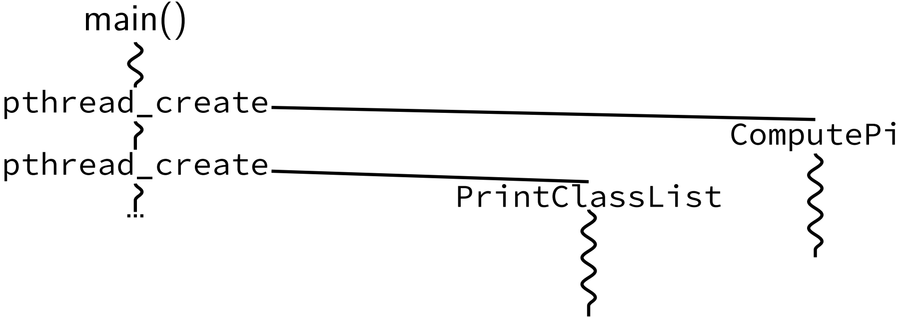
- multiple processors to speed-up simulation (life assignment)

single and multithread processes



pthread_create

```
void *ComputePi(void *argument) { ...  }
void *PrintClassList(void *argument) { ...  }
int main() {
  pthread_t pi_thread, list_thread;
  if (0 != pthread_create(&pi_thread, NULL, ComputePi, NULL))
      handle_error();
  if (0 != pthread_create(&list_thread, NULL, PrintClassList, NULL))
      handle_error();
  ... /* more code */
}
```



pthread_create

```
void *ComputePi(void *argument) { ...  }
void *PrintClassList(void *argument) { ...  }
int main() {
  pthread_t pi_thread, list_thread;
  if (0 != pthread_create(&pi_thread, NULL, ComputePi, NULL))
      handle_error();
  if (0 != pthread_create(&list_thread, NULL, PrintClassList, NULL))
      handle_error();
  ... /* 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;
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pthread_create

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  ... /* more code */
}
```

pthread_create arguments:

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pthread_create

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int main() {
  pthread_t pi_thread, list_thread;
  if (0 != pthread_create(&pi_thread, NULL, ComputePi, NULL))
      handle_error();
  if (0 != pthread_create(&list_thread, NULL, PrintClassList, NULL))
      handle_error();
  ... /* 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

```c
#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;
    /* assume does not fail */
    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.

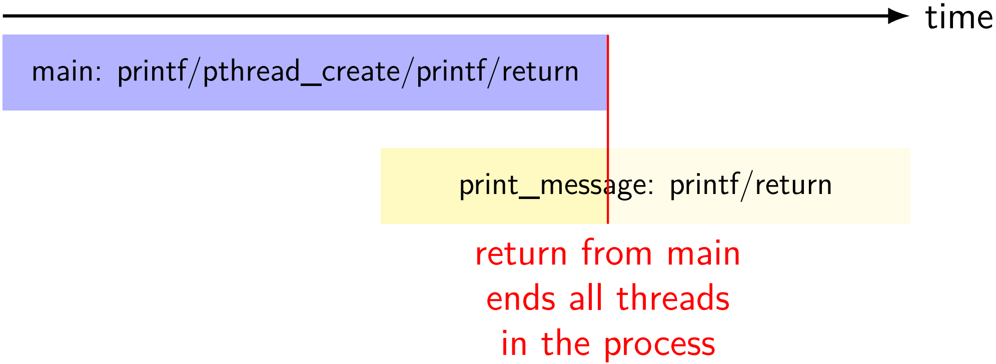
What happened?

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)

```c
#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;
    /* missing: error checking */
    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)

```c
#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;
    /* missing: error checking */
    pthread_create(&the_thread, NULL, print_message, NULL);
    printf("Done starting thread\n");
    pthread_exit(NULL);
}
```

pthread_join, pthread_exit

R = `pthread_join`(X, &P): wait for thread X, copies return value into P

- like `waitpid`, but for a thread
- thread return value is pointer to anything
- R = 0 if successful, error code otherwise

`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

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

pthread_join, pthread_mutex_...(later), ...

will often omit error checking in slides for brevity

error checking pthread_create

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

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;
    /* missing: error handling */
    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 result
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;
    /* missing: error handling */
    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

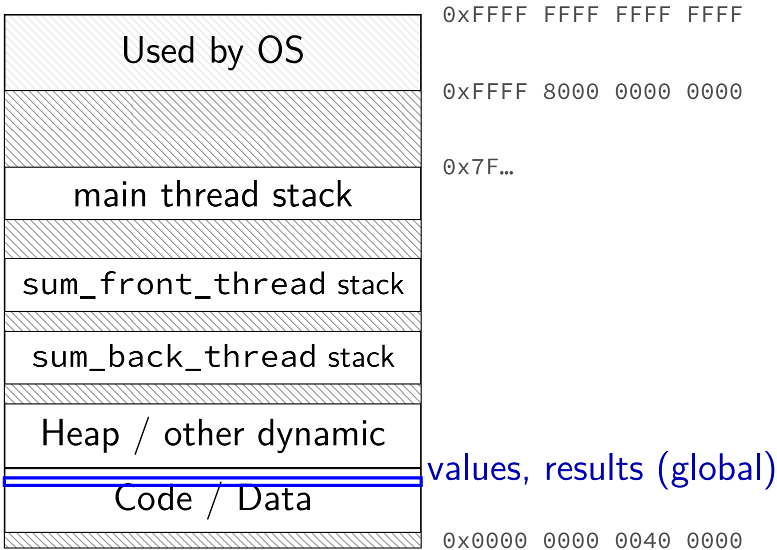
```
int values[1024];   in
void *sum_front(void *
    int sum = 0;
    for (int i = 0; i < 512; ++i) { sum += values[i]; }
    results[0] = sum;
    return NULL;
}
void *sum_back(void *ignored_argument) {
    int sum = 0;
    for (int i = 512; i < 1024; ++i) { sum += values[i]; }
    results[1] = sum;
    return NULL;
}
int sum_all() {
    pthread_t sum_front_thread, sum_back_thread;
    /* missing: error handling */
    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 e

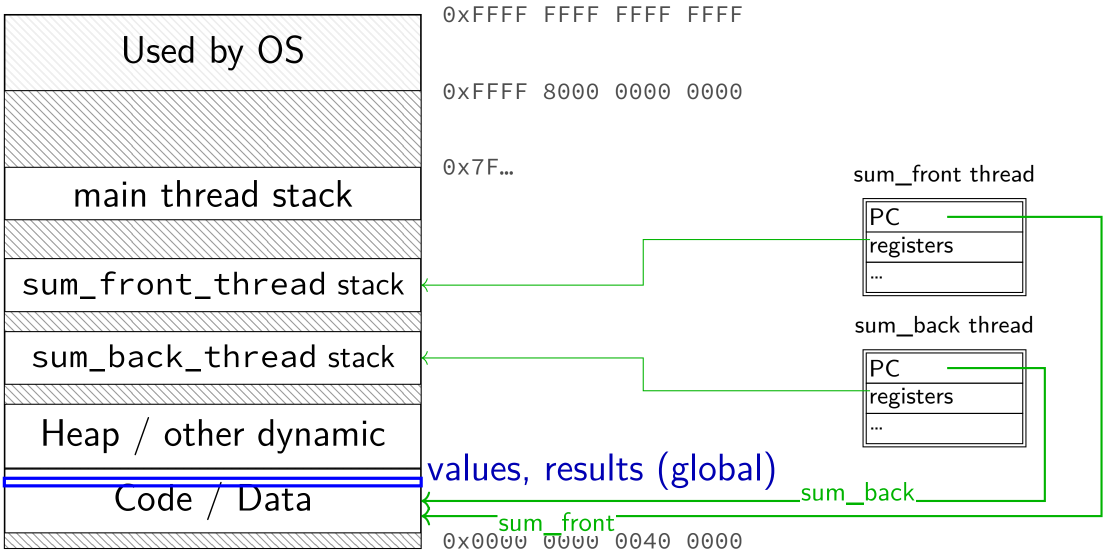
values returned from threads
via global array instead of return value
(partly to illustrate that memory is shared,
partly because this pattern works when we don't join (later))

```
int valu
void *su
    int
    for
    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;
    /* missing: error handling */
    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() {
    /* missing: error handling */
    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)

values, results: global variables — shared

```
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() {
    /* missing: error handling */
    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 (info struct)

```
int values[1024];
struct ThreadInfo {
    int start, end, result;
};
void *sum_thread(void *argument) {
    struct ThreadInfo *my_info =  (struct 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]; struct 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
    int start, end, result;
};
void *sum_thread(void *argument) {
    struct ThreadInfo *my_info =  (struct 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]; struct 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)

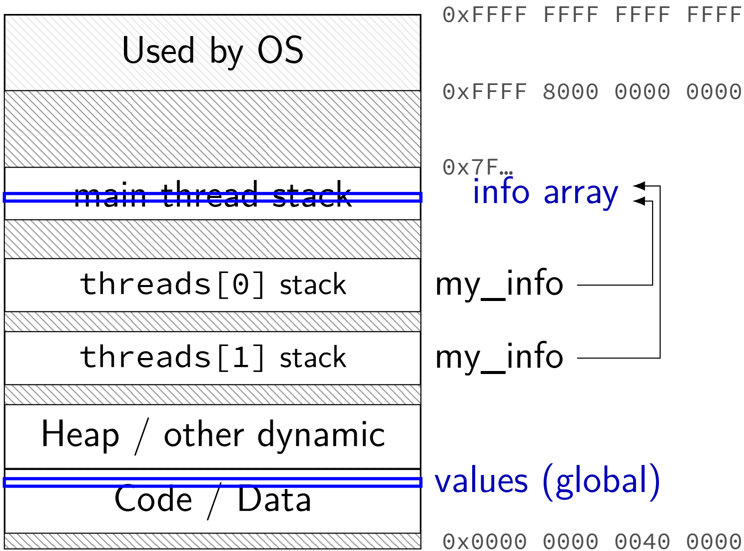
```
int values[1024];
struct ThreadInfo {
    int start, end, result;
};
void *sum_thread(void *argument) {
    struct ThreadInfo *my_info = (struct ThreadInfo *) argument;
    int sum = 0;
    for (int i = my_info->start;                                    ; }
    my_info->result = sum;
    return NULL;
}
int sum_all() {
    pthread_t thread[2]; struct 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) {
    struct ThreadInfo *my_info =  (struct 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]; struct 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;

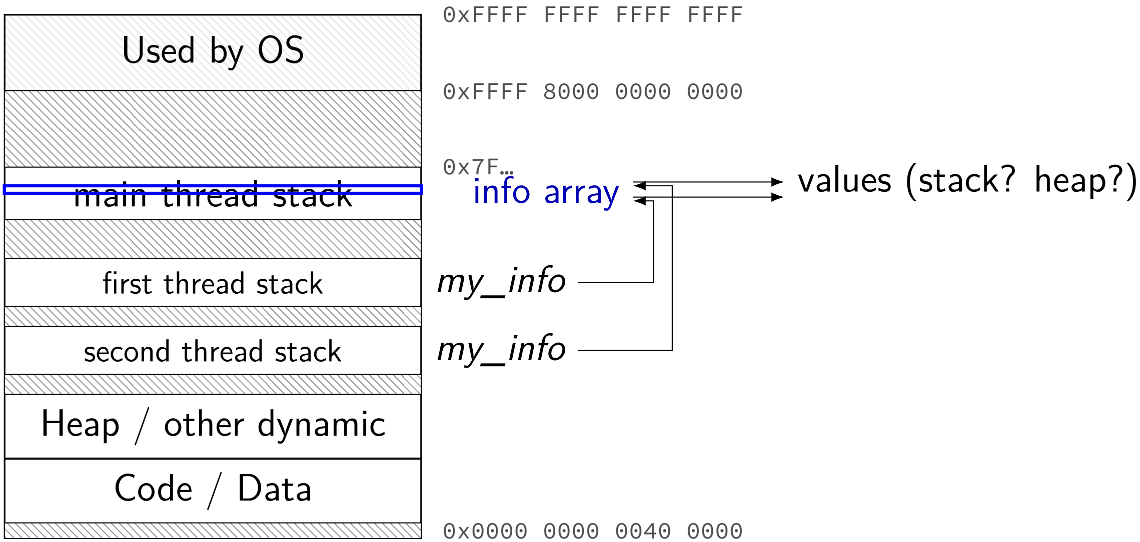
}
int sum_all(int *values) {
    ThreadInfo info[2]; pthread_t thread[2];
    for (int i = 0; i < 2; ++i) {
        info[i].values = values; info[i].start = i*512; info[i].end = (i+1)*512;
        pthread_create(&threads[i], NULL, sum_thread, (void *) &info[i]);
    }
    for (int i = 0; i < 2; ++i)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

struct ThreadInfo *start_sum_all(int *values) {
    struct ThreadInfo *info = calloc(2, sizeof(struct ThreadInfo));
    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;
    free(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) {
    ...
}

struct ThreadInfo *start_sum_all(int *values) {
    struct ThreadInfo *info = calloc(2, sizeof(struct ThreadInfo));
    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);
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    free(info);
    return result;
}
```

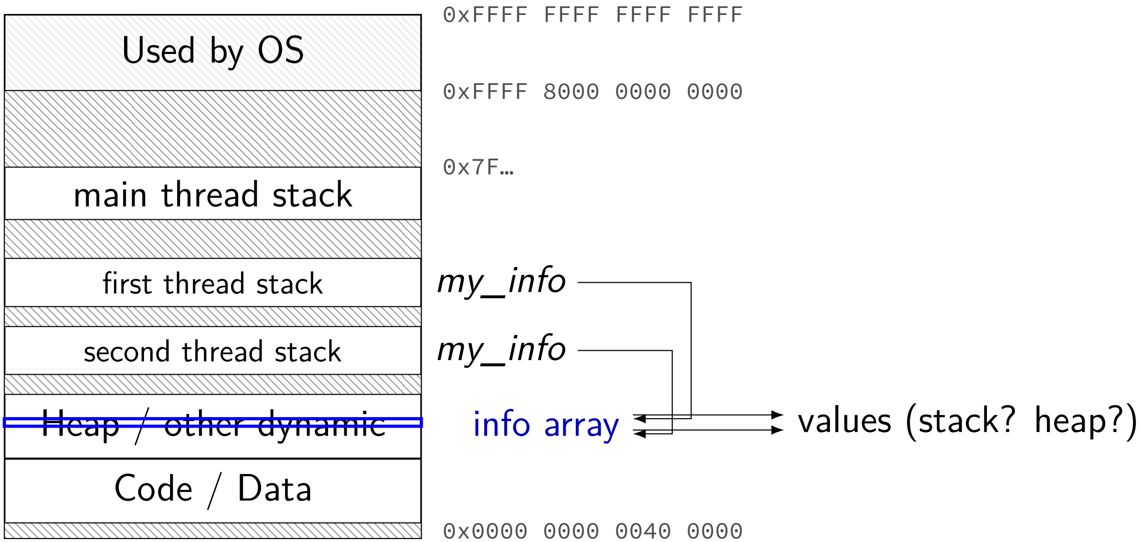
sum example (on heap)

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

struct ThreadInfo *start_sum_all(int *values) {
    struct ThreadInfo *info = calloc(2, sizeof(struct ThreadInfo));
    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;
    free(info);
    return result;
}
```

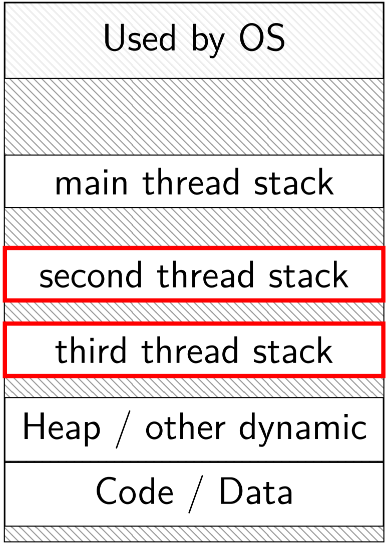
thread_sum memory (heap version)



what's wrong with this?

```
/* omitted: headers */
void *create_string(void *ignored_argument) {
  char string[1024];
  ComputeString(string);
  return string;
}
int main() {
  pthread_t the_thread;
  pthread_create(&the_thread, NULL, create_string, NULL);
  char *string_ptr;
  pthread_join(the_thread, (void**) &string_ptr);
  printf("string␣is␣%s\n", string_ptr);
}
```

program memory



`0xFFFF FFFF FFFF FFFF`

`0xFFFF 8000 0000 0000`

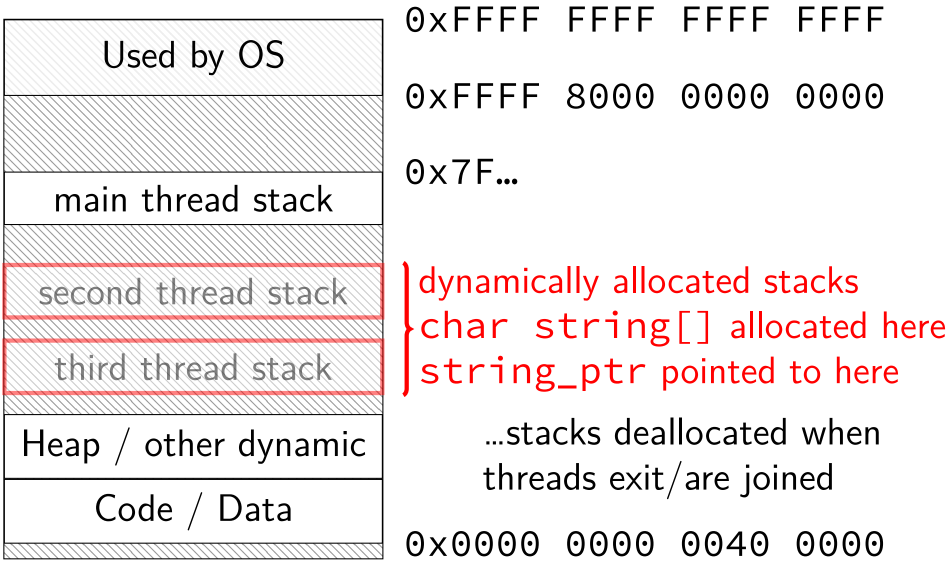
`0x7F`...

dynamically allocated stacks
`char string[]` allocated here
`string_ptr` pointed to here

...stacks deallocated when threads exit/are joined

`0x0000 0000 0040 0000`

program memory



thread joining

pthread_join allows collecting thread return value

if you don't join joinable thread, then memory leak!

thread joining

pthread_join allows collecting thread return value

if you don't join joinable thread, then memory leak!

avoiding memory leak?

always join…or

"detach" thread to make it not joinable

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 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;
    /* assume does not fail */
    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.

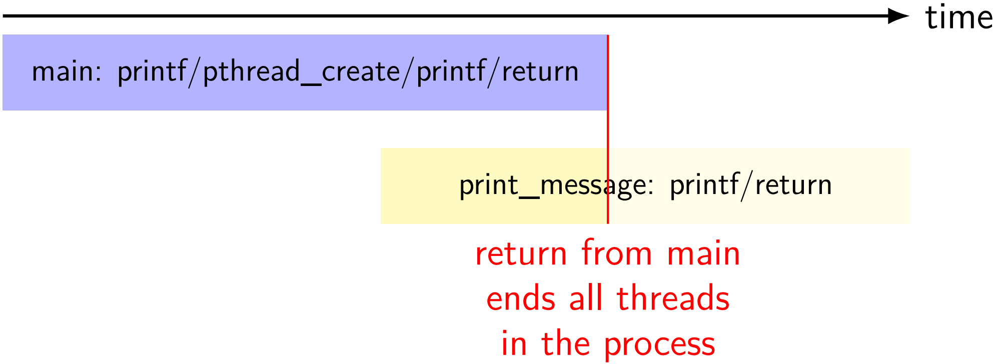
What happened?

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?



the correctness problem

two threads?

introduces *non-determinism*

which one runs first?

allows for “race condition” bugs

…to be avoided with synchronization constructs

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(accountNumber);
    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

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	`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

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 (2)

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)

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 (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 (2)

possible values of x? (initially $x = y = 0$)

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

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 $\approx$ address of word is multiple of word size (typically done by compilers)

but some instructions are not atomic; examples:

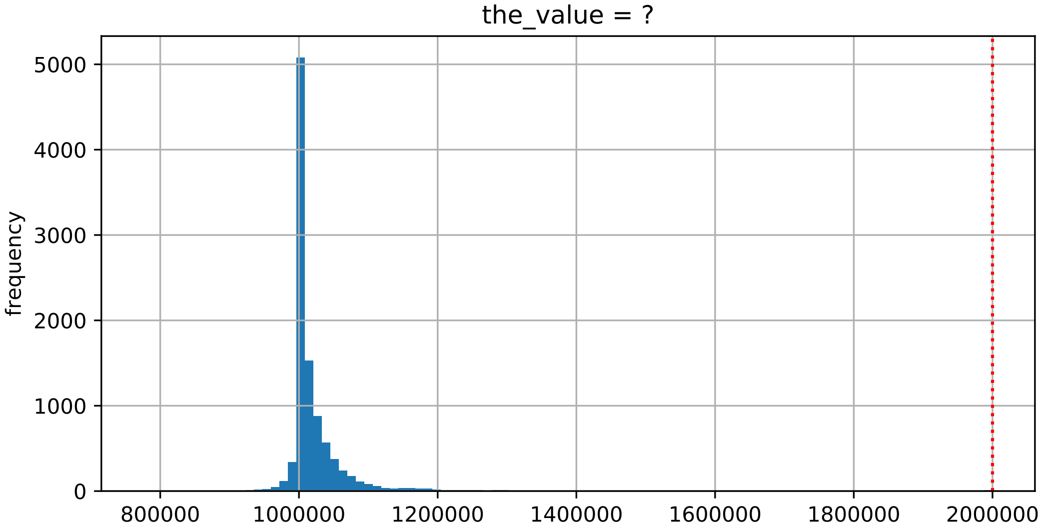
- x86: integer `add` constant to memory location
- many CPUs: loading/storing values that cross cache blocks
  - e.g. if cache blocks `0x40` bytes, load/store 4 byte from addr. `0x3E` is not atomic

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

compilers move loads/stores (1)

```
void WaitForReady() {
    do {} while (!ready);
}
```

```
WaitForOther:
  movl ready, %eax  // eax <- other_ready
.L2:
  testl %eax, %eax
  je .L2                     // while (eax == 0) repeat
  ...
```

compilers move loads/stores (1)

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void WaitForReady() {
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}
```

```
WaitForOther:
  movl ready, %eax  // eax <- other_ready
.L2:
  testl %eax, %eax
  je .L2                  // while (eax == 0) repeat
  ...
```

compilers move loads/stores (2)

```
void WaitForOther() {
    is_waiting = 1;
    do {} while (!other_ready);
    is_waiting = 0;
}
```

```
WaitForOther:
  // compiler optimization: don't set is_waiting to 1,
  // (why? it will be set to 0 anyway)
  movl other_ready, %eax  // eax <- other_ready
.L2:
  testl %eax, %eax
  je .L2                           // while (eax == 0) repeat
  ...
  movl $0, is_waiting  // is_waiting <- 0
```

compilers move loads/stores (2)

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void WaitForOther() {
    is_waiting = 1;
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```

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  testl %eax, %eax
  je .L2                     // while (eax == 0) repeat
  ...
  movl $0, is_waiting  // is_waiting <- 0
```

compilers move loads/stores (2)

```
void WaitForOther() {
    is_waiting = 1;
    do {} while (!other_ready);
    is_waiting = 0;
}
```

```
WaitForOther:
  // compiler optimization: don't set is_waiting to 1,
  // (why? it will be set to 0 anyway)
  movl other_ready, %eax   // eax <- other_ready
.L2:
  testl %eax, %eax
  je .L2                        // while (eax == 0) repeat
  ...
  movl $0, is_waiting  // is_waiting <- 0
```

fixing compiler reordering?

isn't there a way to tell compiler not to do these optimizations?

yes, but that is still not enough!

processors sometimes do this kind of reordering too (between cores)

pthreads and reordering

many pthreads functions prevent reordering

- everything before function call actually happens before

includes preventing some optimizations

- e.g. keeping global variable in register for too long

pthread_create, pthread_join, other tools we'll talk about …

- basically: if pthreads is waiting for/starting something, no weird ordering

implementation part 1: prevent compiler reordering

implementation part 2: use special instructions

- example: x86 `mfence` instruction

some definitions

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

like updating shared balance

some definitions

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

- like updating shared balance

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

- result of mutual exclusion

some definitions

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

- like updating shared balance

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

- result of mutual exclusion

lock: object only one thread can hold at a time

- interface for creating critical sections

lock analogy

agreement: only change account balances while wearing this hat

normally hat kept on table

put on hat when editing balance

hopefully, only one person (= thread) can wear hat a time

need to wait for them to remove hat to put it on

lock analogy

agreement: only change account balances while wearing this hat

normally hat kept on table

put on hat when editing balance

hopefully, only one person (= thread) can wear hat a time

need to wait for them to remove hat to put it on

"lock (or acquire) the lock" = get and put on hat

"unlock (or release) the lock" = put hat back on table

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(account_lock);
balance += ...;
Unlock(account_lock);
```

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(account_lock);
balance += ...;
Unlock(account_lock);
```

waiting for lock?

when waiting — ideally:

not using processor (at least if waiting a while)

OS can context switch to other programs

pthread mutex

```
#include <pthread.h>

pthread_mutex_t account_lock;
pthread_mutex_init(&account_lock, NULL);
    // or: pthread_mutex_t account_lock =
    //               PTHREAD_MUTEX_INITIALIZER;
...
pthread_mutex_lock(&account_lock);
balance += ...;
pthread_mutex_unlock(&account_lock);
```

exercise

```
pthread_mutex_t lock1 = PTHREAD_MUTEX_INITIALIZER;
pthread_mutex_t lock2 = PTHREAD_MUTEX_INITIALIZER;
string one = "init␣one", two = "init␣two";
void ThreadA() {
    pthread_mutex_lock(&lock1);
    one = "one␣in␣ThreadA";  // (A1)
    pthread_mutex_unlock(&lock1);
    pthread_mutex_lock(&lock2);
    two = "two␣in␣ThreadA";  // (A2)
    pthread_mutex_unlock(&lock2);
}
void ThreadB() {
    pthread_mutex_lock(&lock1);
    one = "one␣in␣ThreadB";  // (B1)
    pthread_mutex_lock(&lock2);
    two = "two␣in␣ThreadB";  // (B2)
    pthread_mutex_unlock(&lock2);
    pthread_mutex_unlock(&lock1);
}
```

possible values of one/two after A+B run?

exercise (alternate 1)

```
pthread_mutex_t lock1 = PTHREAD_MUTEX_INITIALIZER;
pthread_mutex_t lock2 = PTHREAD_MUTEX_INITIALIZER;
string one = "init␣one", two = "init␣two";
void ThreadA() {
    pthread_mutex_lock(&lock2);
    two = "two␣in␣ThreadA";  // (A2)
    pthread_mutex_unlock(&lock2);
    pthread_mutex_lock(&lock1);
    one = "one␣in␣ThreadA";  // (A1)
    pthread_mutex_unlock(&lock1);
}
void ThreadB() {
    pthread_mutex_lock(&lock1);
    one = "one␣in␣ThreadB";  // (B1)
    pthread_mutex_lock(&lock2);
    two = "two␣in␣ThreadB";  // (B2)
    pthread_mutex_unlock(&lock2);
    pthread_mutex_unlock(&lock1);
}
```

possible values of one/two after A+B run?

exercise (alternate 2)

```
pthread_mutex_t lock1 = PTHREAD_MUTEX_INITIALIZER;
pthread_mutex_t lock2 = PTHREAD_MUTEX_INITIALIZER;
string one = "init␣one", two = "init␣two";
void ThreadA() {
    pthread_mutex_lock(&lock2);
    two = "two␣in␣ThreadA";  // (A2)
    pthread_mutex_unlock(&lock2);
    pthread_mutex_lock(&lock1);
    one = "one␣in␣ThreadA";  // (A1)
    pthread_mutex_unlock(&lock1);
}
void ThreadB() {
    pthread_mutex_lock(&lock1);
    one = "one␣in␣ThreadB";  // (B1)
    pthread_mutex_unlock(&lock1);
    pthread_mutex_lock(&lock2);
    two = "two␣in␣ThreadB";  // (B2)
    pthread_mutex_unlock(&lock2);
}
```

possible values of one/two after A+B run?

POSIX mutex restrictions

pthread_mutex rule: unlock from same thread you lock in

does this actually matter?

depends on how pthread_mutex is implemented

preview: general sync

lots of coordinating threads beyond locks

will talk about two general tools later:k

- monitors/condition variables
- semaphores [if time]

big added feature: wait for arbitrary thing to happen

also some less general tools: barriers

a bad idea

one bad idea to wait for an event:

```
pthread_mutex_t lock = PTHREAD_MUTEX_INITIALIZER; bool ready = false;
void WaitForReady() {
    pthread_mutex_lock(&lock);
    do {
        pthread_mutex_unlock(&lock);
        /* only time MarkReady() can run */
        pthread_mutex_lock(&lock);
    } while (!ready);
    pthread_mutex_unlock(&lock);
}
void MarkReady() {
    pthread_mutex_lock(&lock);
    ready = true;
    pthread_mutex_unlock(&lock);
}
```

DO NOT USE THIS CODE

wastes processor time; MarkReady can stall waiting for unlock window

beyond locks

in practice: want more than locks for synchronization

for waiting for arbtirary events (without CPU-hogging-loop):

- monitors
- semaphores

for common synchornization patterns:

- barriers
- reader-writer locks

higher-level interface:

- transactions

barriers

compute minimum of 100M element array with 2 processors

algorithm:

compute minimum of 50M of the elements on each CPU
- one thread for each CPU

wait for all computations to finish

take minimum of all the minimums

barriers

compute minimum of 100M element array with 2 processors

algorithm:

compute minimum of 50M of the elements on each CPU

- one thread for each CPU

wait for all computations to finish

take minimum of all the minimums

barriers API

barrier.Initialize(NumberOfThreads)

barrier.Wait() — return after all threads have waited

idea: multiple threads perform computations in parallel

threads wait for all other threads to call Wait()

barrier: waiting for finish

```
barrier.Initialize(2);
```

Thread 0

```
partial_mins[0] =
    /* min of first
       50M elems */;

barrier.Wait();


total_min = min(
    partial_mins[0],
    partial_mins[1]
);
```

Thread 1

```
partial_mins[1] =
    /* min of last
       50M elems */
barrier.Wait();
```

barriers: reuse

Thread 0

```
results[0][0] = getInitial(0);
barrier.Wait();

results[1][0] =
    computeFrom(0,
        results[0][0],
        results[0][1]
    );
barrier.Wait();

results[2][0] =
    computeFrom(0,
        results[1][0],
        results[1][1]
    );
```

Thread 1

```
results[0][1] = getInitial(1);
barrier.Wait();

results[1][1] =
    computeFrom(1,
        results[0][0],
        results[0][1]
    );
barrier.Wait();

results[2][1] =
    computeFrom(1,
        results[1][0],
        results[1][1]
    );
```

barriers: reuse

Thread 0

```
results[0][0] = getInitial(0);
barrier.Wait();

results[1][0] =
    computeFrom(0,
        results[0][0],
        results[0][1]
    );
barrier.Wait();

results[2][0] =
    computeFrom(0,
        results[1][0],
        results[1][1]
    );
```

Thread 1

```
results[0][1] = getInitial(1);
barrier.Wait();

results[1][1] =
    computeFrom(1,
        results[0][0],
        results[0][1]
    );
barrier.Wait();

results[2][1] =
    computeFrom(1,
        results[1][0],
        results[1][1]
    );
```

barriers: reuse

Thread 0

```
results[0][0] = getInitial(0);
barrier.Wait();

results[1][0] =
    computeFrom(0,
        results[0][0],
        results[0][1]
    );
barrier.Wait();

results[2][0] =
    computeFrom(0,
        results[1][0],
        results[1][1]
    );
```

Thread 1

```
results[0][1] = getInitial(1);
barrier.Wait();

results[1][1] =
    computeFrom(1,
        results[0][0],
        results[0][1]
    );
barrier.Wait();

results[2][1] =
    computeFrom(1,
        results[1][0],
        results[1][1]
    );
```

pthread barriers

```
pthread_barrier_t barrier;
pthread_barrier_init(
    &barrier,
    NULL /* attributes */,
    numberOfThreads
);
...
...
pthread_barrier_wait(&barrier);
```

exercise

```
pthread_barrier_t barrier; int x = 0, y = 0;
void thread_one() {
    y = 10;
    pthread_barrier_wait(&barrier);
    y = x + y;
    pthread_barrier_wait(&barrier);
    pthread_barrier_wait(&barrier);
    printf("%d␣%d\n", x, y);
}
void thread_two() {
    x = 20;
    pthread_barrier_wait(&barrier);
    pthread_barrier_wait(&barrier);
    x = x + y;
    pthread_barrier_wait(&barrier);
}
```

output? (if both run at once, barrier set for 2 threads)

life homework (pseudocode)

```
for (int time = 0; time < MAX_ITERATIONS; ++time) {
    for (int y = 0; y < size; ++y) {
        for (int x = 0; x < size; ++x) {
            to_grid(x, y) = computeValue(from_grid, x, y);
        }
    }
    swap(from_grid, to_grid);
}
```

life homework

compute grid of values for time t from grid for time $t-1$

compute new value at i, j based on surrounding values

parallel version: produce parts of grid in different threads

use barriers to finish time t before going to time $t+1$

backup slides