last time

cache misses and C code

- size of way = distance between same set

K-way set-associative caches

- like K direct-mapped caches 'stapled together'
- still divide addresses into tag/index/offset
- index identifies set with K blocks
- store valid bit+tag for each block

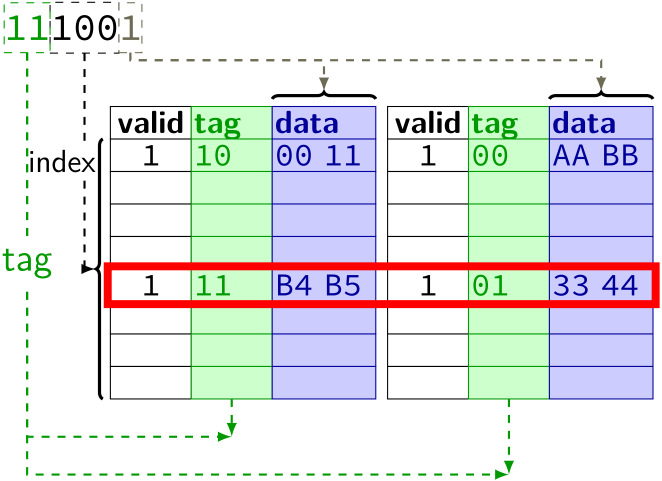
replacement policies least recently used + related

anonymous feedback (1)

"Can you explain the role of the index in a 2 way cache? It seems like since a miss with index 1 can be put into index 0 row."

the way we've drawn 2-way caches, they have *two columns* (ways)
index says which row — so miss with index 1 can only go in index 0 row
…but could go in either column (depending on replacement policy)

cache operation (associative)



anonymous feedback (2)

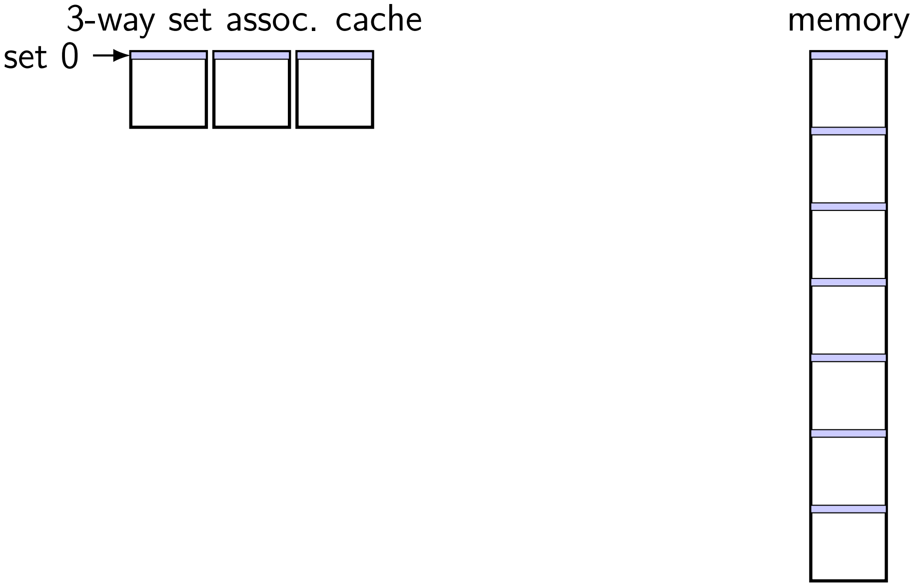
"I think I speak for a lot of students when I say it doesn't feel like you're listening to our anonymous feedback. It seems like you're just posting a few on the lecture slides to give an excuse or invalidate our concerns, and not actually using it to evaluate the course and make changes where necessary. This course is extremely new, and it's expected that changes will have to be made. Here are some examples of changes that students have proposed that you've not taken: the labs are essentially a second homework and need to be started days in advance (which isn't what a 75-minute lab is meant to be); the readings are extremely disorganized and often make us more confused; and so much more."

indeed, often not doing something about it this semester (mostly because of worries about last-minute changes/small sample size of feedback)

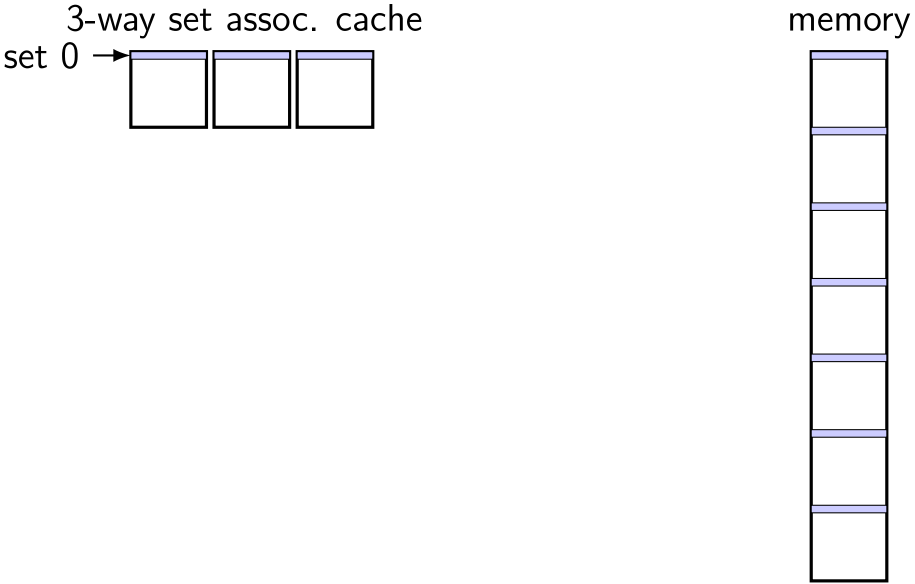
re: labs too much — I don't know what labs besides signal+possibly make fit this description

re: readings — agree that there's work there, making small

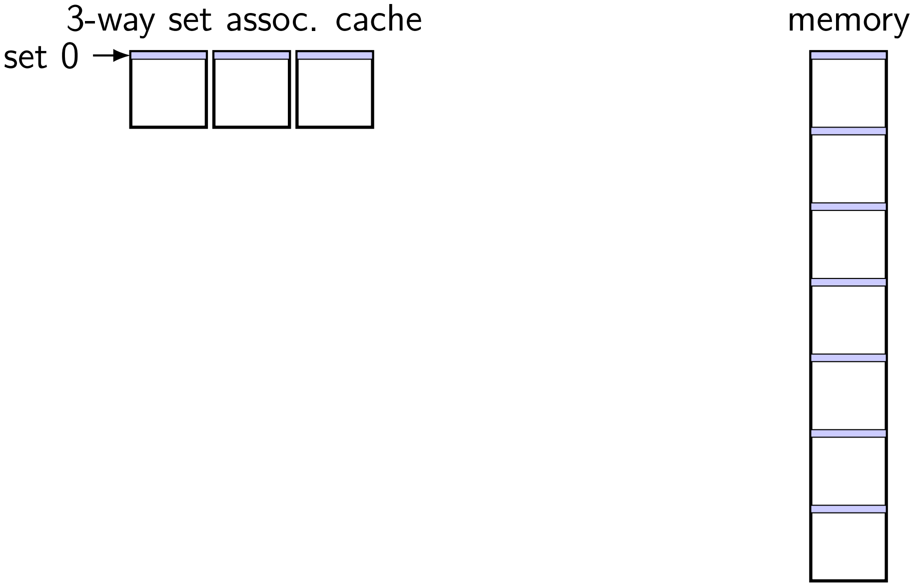
mapping of sets to memory (3-way)



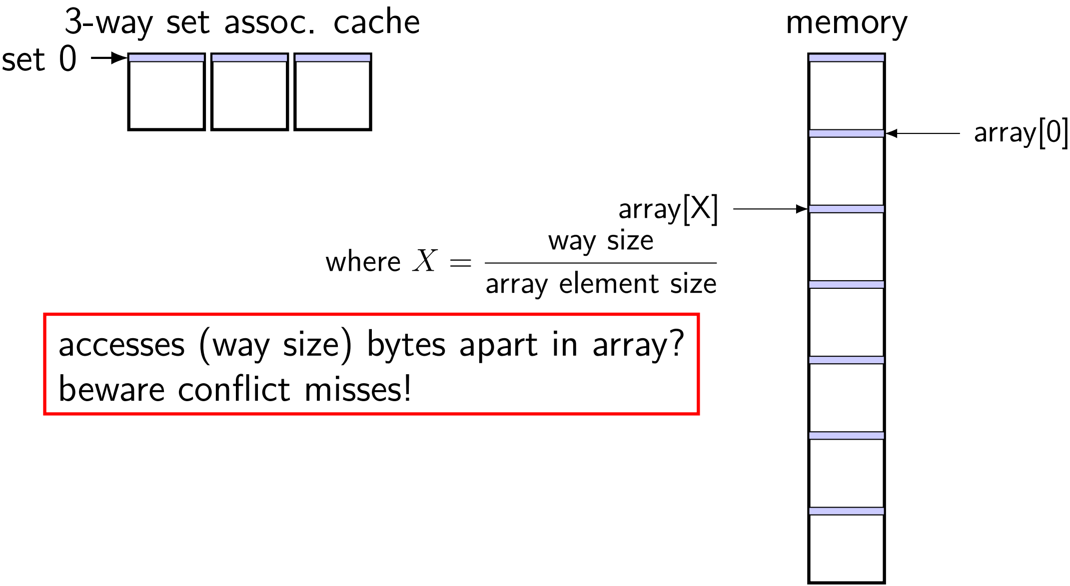
mapping of sets to memory (3-way)



mapping of sets to memory (3-way)



mapping of sets to memory (3-way)



where $X = \dfrac{\text{way size}}{\text{array element size}}$

accesses (way size) bytes apart in array?
beware conflict misses!

handling writes

what about writing to the cache?

two decision points:

if the value is not in cache, do we add it?

- if yes: need to load rest of block — *write-allocate*
- if no: missing out on locality? *write-no-allocate*

if value is in cache, when do we update next level?

- if immediately: extra writing *write-through*
- if later: need to remember to do so *write-back*

allocate on write?

processor writes less than whole cache block

block not yet in cache

two options:

write-allocate

fetch rest of cache block, replace written part
(then follow write-through or write-back policy)

write-no-allocate

don't use cache at all (send write to memory *instead*)
guess: not read soon?

allocate on write?

processor writes less than whole cache block

block not yet in cache

two options:

write-allocate

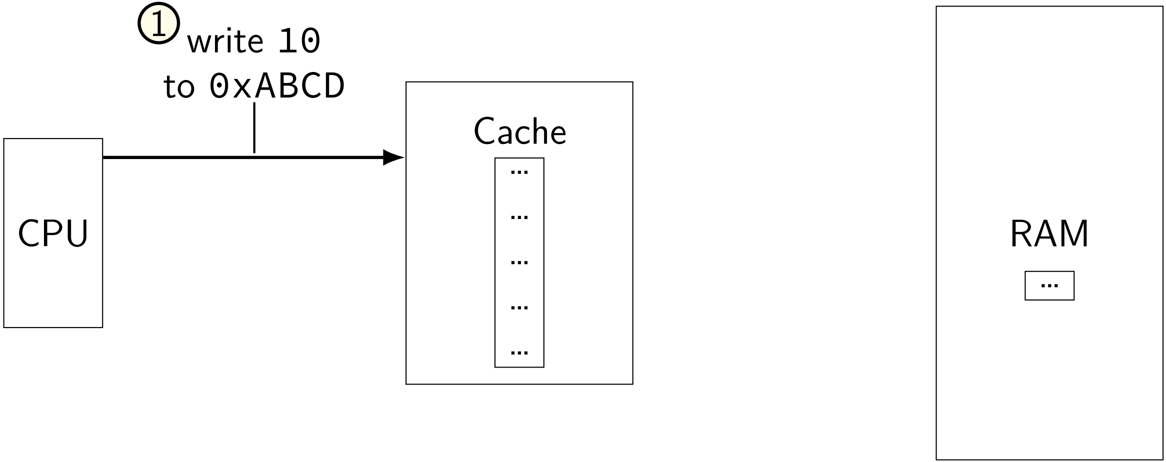
fetch rest of cache block, replace written part
(then follow write-through or write-back policy)

write-no-allocate

don't use cache at all (send write to memory *instead*)
guess: not read soon?

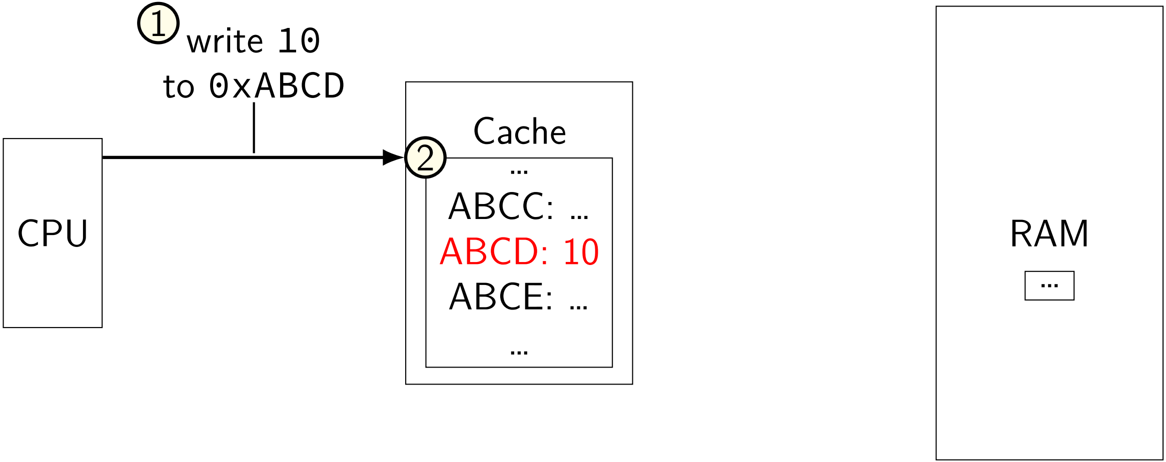
write-allocate v. write-no-allocate

option 1: write-allocate

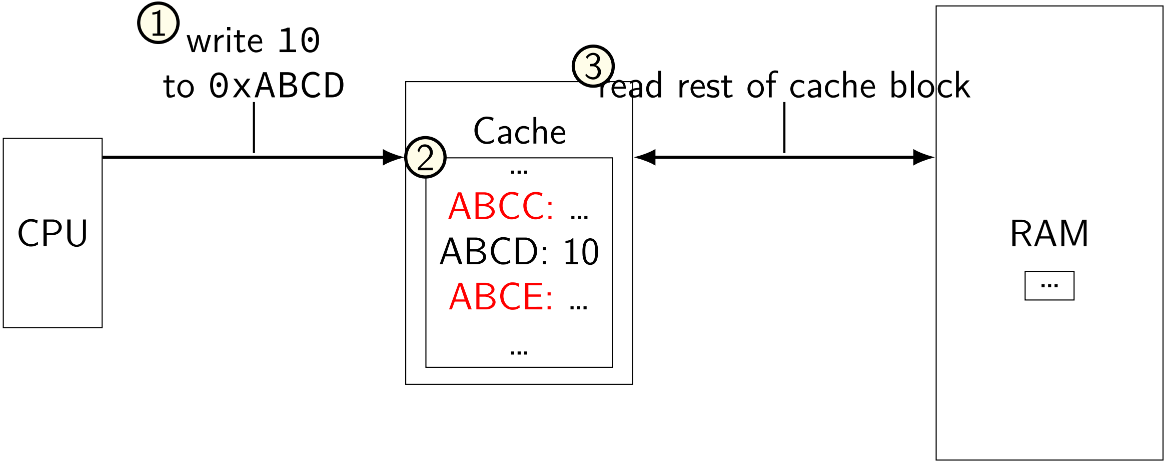


write-allocate v. write-no-allocate

option 1: write-allocate

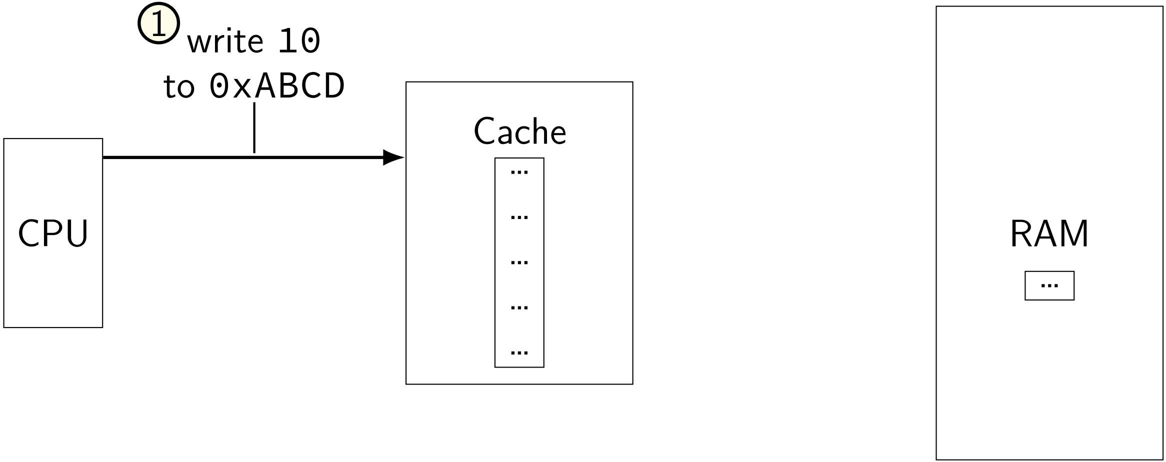


write-allocate v. write-no-allocate



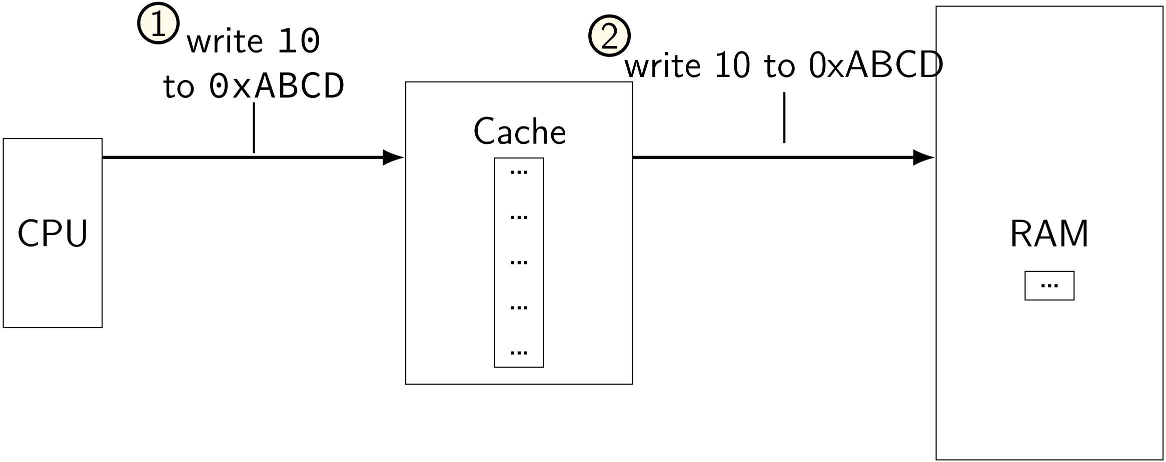
write-allocate v. write-no-allocate

option 2: write-no-allocate



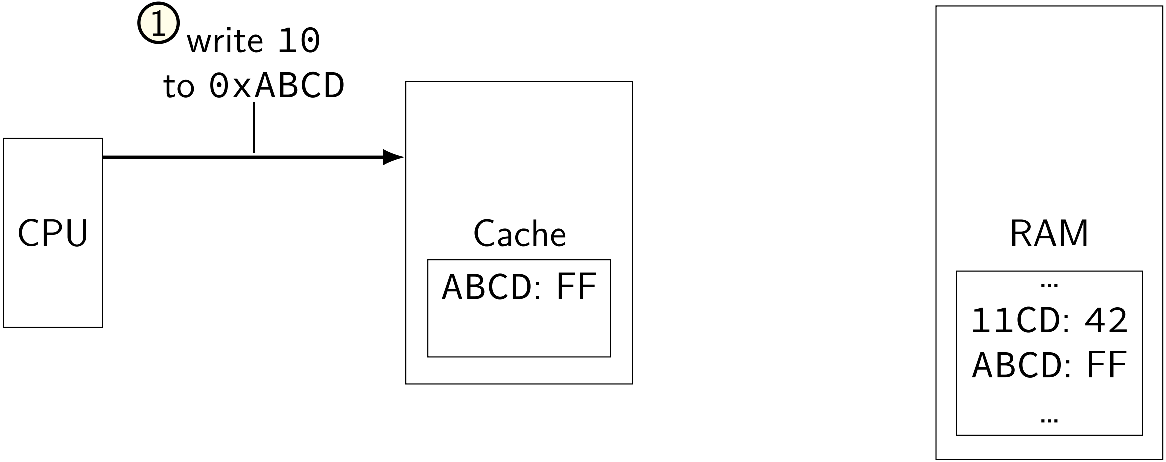
write-allocate v. write-no-allocate

option 2: write-no-allocate



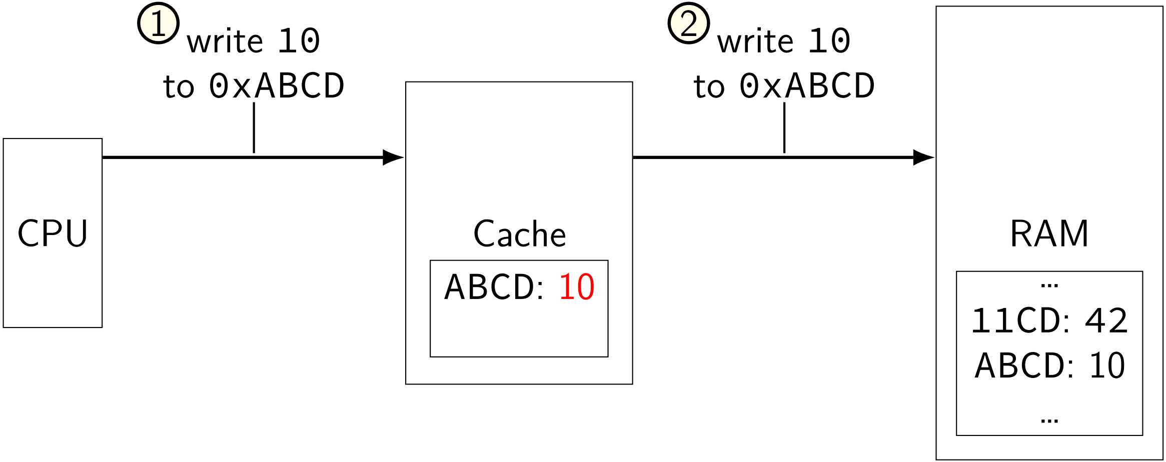
write-through v. write-back

option 1: write-through



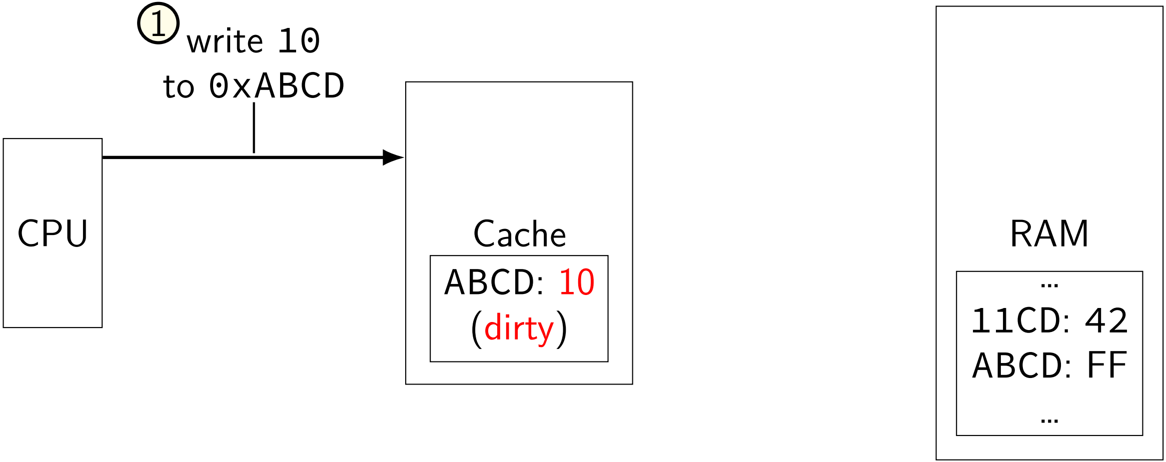
write-through v. write-back

option 1: write-through

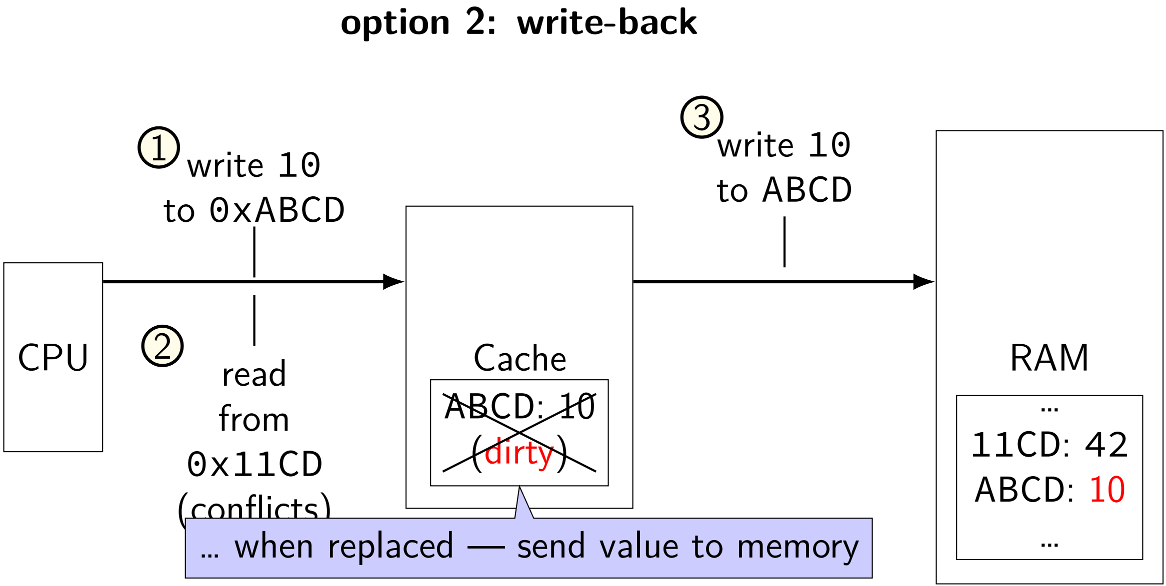


write-through v. write-back

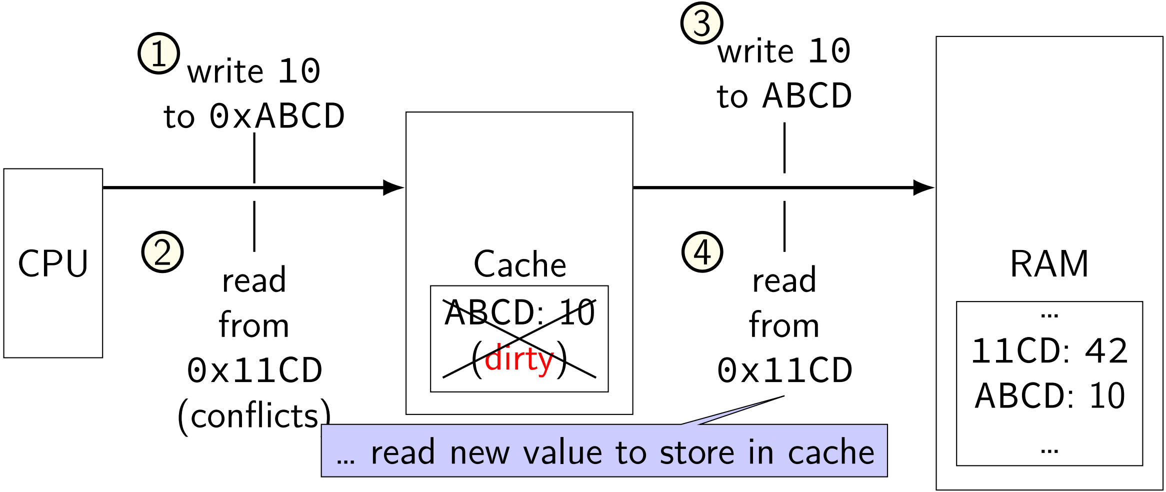
option 2: write-back



write-through v. write-back



write-through v. write-back



writeback policy

changed value!

2-way set associative, 4 byte blocks, 2 sets

index	valid	tag	value	dirty	valid	tag	value	dirty	LRU
0	1	000000	mem[0x00] mem[0x01]	0	1	011000	mem[0x60]* mem[0x61]*	1	1
1	1	011000	mem[0x62] mem[0x63]	0	0				0

$1 =$ dirty (different than memory)
needs to be written if evicted

write-allocate + write-back

2-way set associative, LRU, writeback

index	valid	tag	value	dirty	valid	tag	value	dirty	LRU
0	1	000000	mem[0x00] mem[0x01]	0	1	011000	mem[0x60]* mem[0x61]*	1	1
1	1	011000	mem[0x62] mem[0x63]	0	0				0

writing 0xFF into address 0x04?

index 0, tag 000001

write-allocate + write-back

2-way set associative, LRU, writeback

index	valid	tag	value	dirty	valid	tag	value	dirty	LRU
0	1	000000	mem[0x00] mem[0x01]	0	1	011000	mem[0x60]* mem[0x61]*	1	1
1	1	011000	mem[0x62] mem[0x63]	0	0				0

writing 0xFF into address `0x04`?

index 0, tag 000001

step 1: find least recently used block

write-allocate + write-back

2-way set associative, LRU, writeback

index	valid	tag	value	dirty	valid	tag	value	dirty	LRU
0	1	000000	mem[0x00] mem[0x01]	0	1	011000	mem[0x60]* mem[0x61]*	~~1~~	1
1	1	011000	mem[0x62] mem[0x63]	0	0				0

writing 0xFF into address `0x04`?

index 0, tag 000001

step 1: find least recently used block

step 2: possibly writeback old block

write-allocate + write-back

2-way set associative, LRU, writeback

index	valid	tag	value	dirty	valid	tag	value	dirty	LRU
0	1	000000	mem[0x00] mem[0x01]	0	1	000001	0xFF mem[0x05]	1	0
1	1	011000	mem[0x62] mem[0x63]	0	0				0

writing 0xFF into address `0x04`?

index 0, tag 000001

step 1: find least recently used block

step 2: possibly writeback old block

step 3a: read in new block – to get mem[0x05]

step 3b: update LRU information

write-no-allocate + write-back

2-way set associative, LRU, writeback

index	valid	tag	value	dirty	valid	tag	value	dirty	LRU
0	1	000000	mem[0x00] mem[0x01]	0	1	011000	mem[0x60]* mem[0x61]*	1	1
1	1	011000	mem[0x62] mem[0x63]	0	0				0

writing 0xFF into address `0x04`?

step 1: is it in cache yet?

step 2: no, just send it to memory

exercise (1)

2-way set associative, LRU, write-allocate, writeback

index	valid	tag	value	dirty	valid	tag	value	dirty	LRU
0	1	001100	mem[0x30] mem[0x31]	0	1	010000	mem[0x40]* mem[0x41]*	1	0
1	1	011000	mem[0x62] mem[0x63]	0	1	001100	mem[0x32]* mem[0x33]*	1	1

for each of the following accesses, performed alone, would it require (a) reading a value from memory (or next level of cache) and (b) writing a value to the memory (or next level of cache)?

writing 1 byte to 0x33
reading 1 byte from 0x52
reading 1 byte from 0x50

exercise (2)

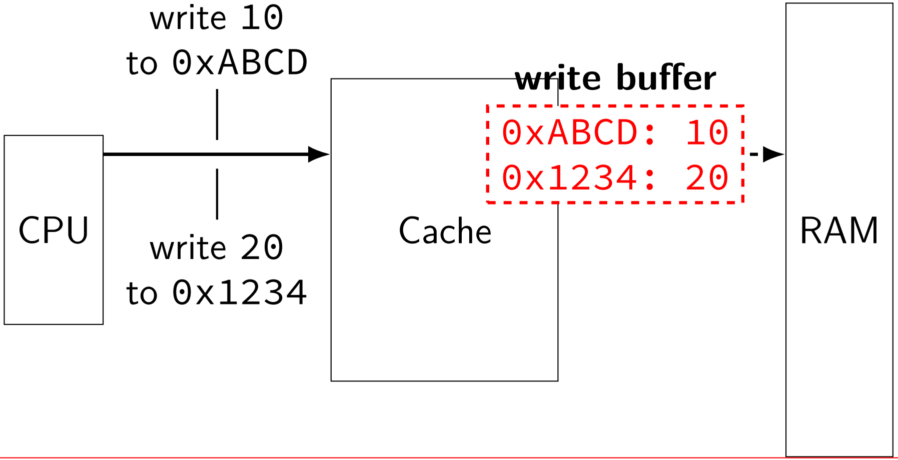
2-way set associative, LRU, write-no-allocate, write-through

index	valid	tag	value	valid	tag	value	LRU
0	1	`001100`	`mem[0x30]` `mem[0x31]`	1	`010000`	`mem[0x40]` `mem[0x41]`	0
1	1	`011000`	`mem[0x62]` `mem[0x63]`	1	`001100`	`mem[0x32]` `mem[0x33]`	1

for each of the following accesses, performed alone, would it require (a) reading a value from memory and (b) writing a value to the memory?

- writing 1 byte to 0x33
- reading 1 byte from 0x52
- reading 1 byte from 0x50

fast writes



write appears to complete immediately when placed in buffer
memory can be much slower

cache tradeoffs briefly

deciding cache size, associativity, etc.?

lots of tradeoffs:

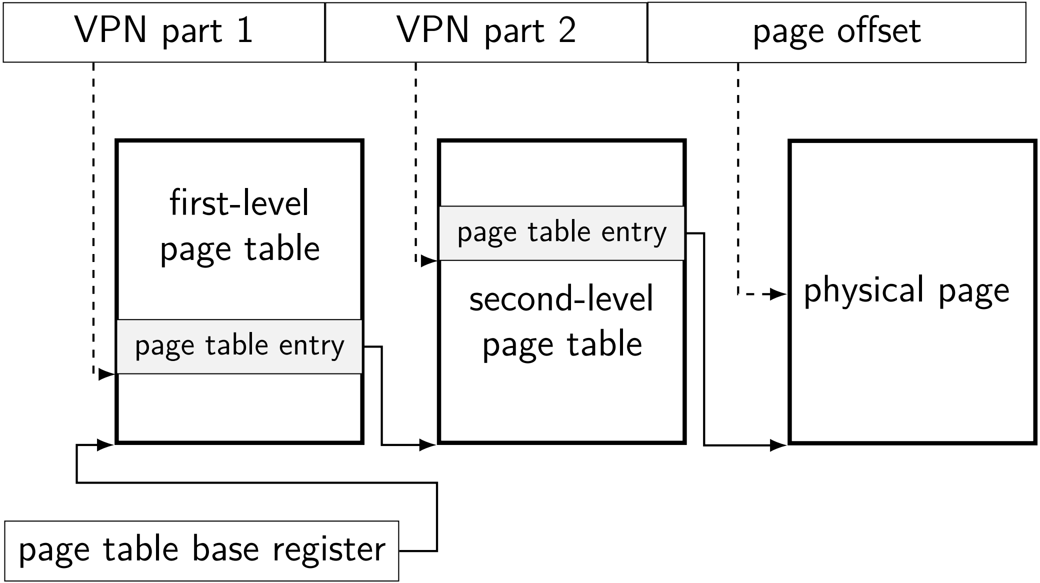
- more cache hits v. slower cache hits?
- faster cache hits v. fewer cache hits?
- more cache hits v. slower cache misses?
- ...

details depend on programs run

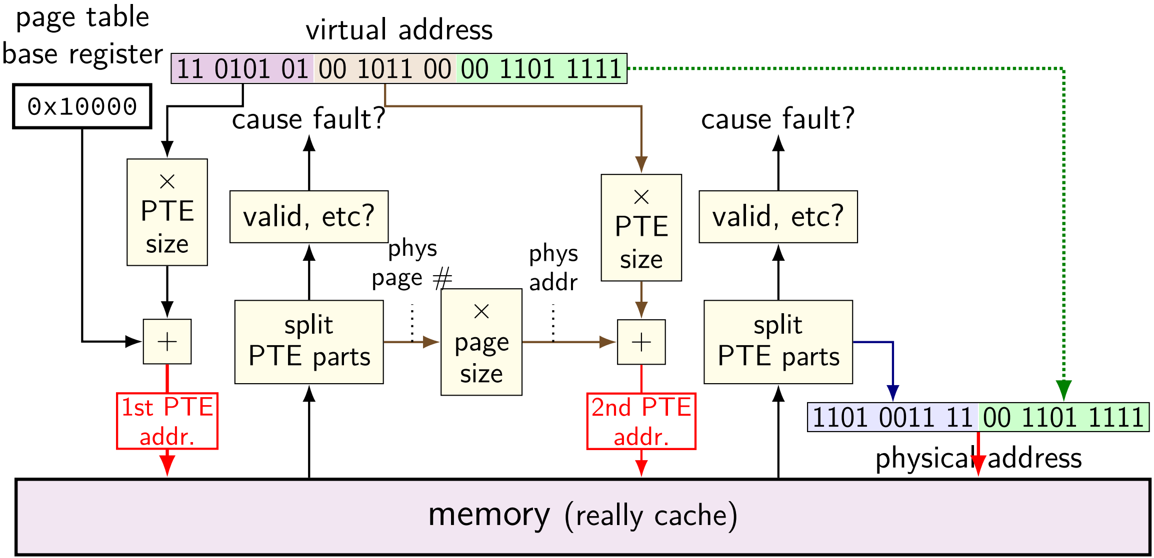
- how often is same block used again?
- how often is same index bits used?

simulation to assess impact of designs

another view



two-level page table lookup



cache accesses and multi-level PTs

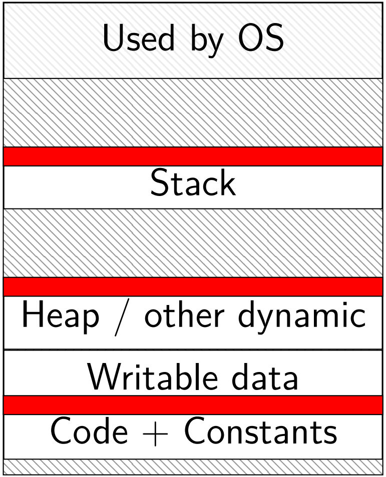
four-level page tables — five cache accesses per program memory access

L1 cache hits — typically a couple cycles each?

so add 8 cycles to each program memory access?

not acceptable

program memory active sets



0xFFFF FFFF FFFF FFFF

0xFFFF 8000 0000 0000

0x7F...

small areas of memory active at a time

one or two pages in each area?

0x0000 0000 0040 0000

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)

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)

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)

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)

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)

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)

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

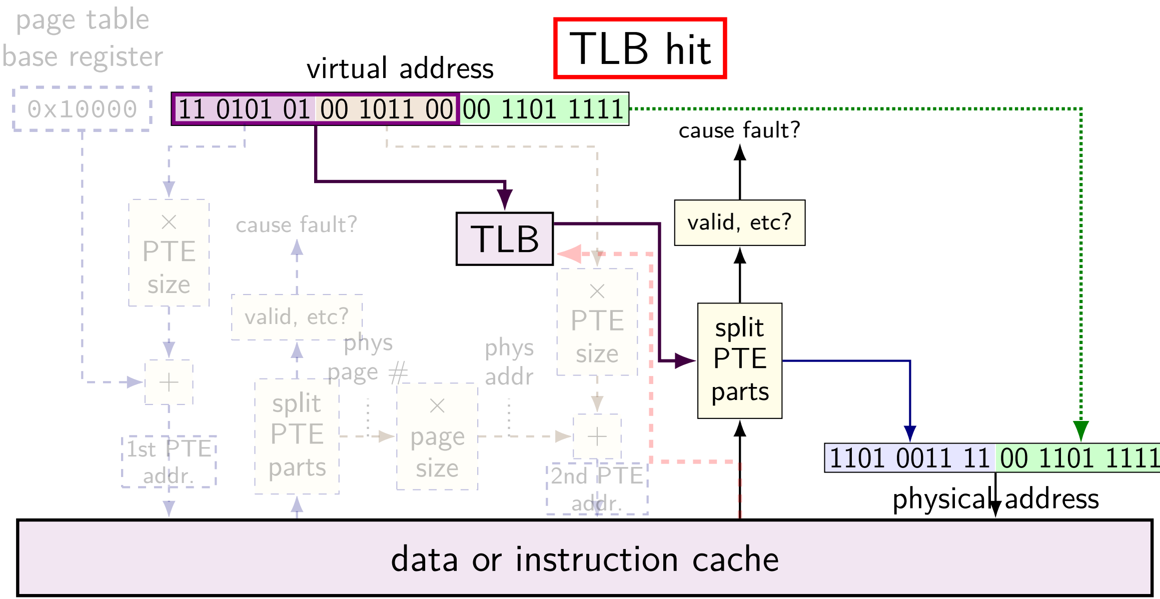
TLB and multi-level page tables

TLB caches valid last-level page table entries

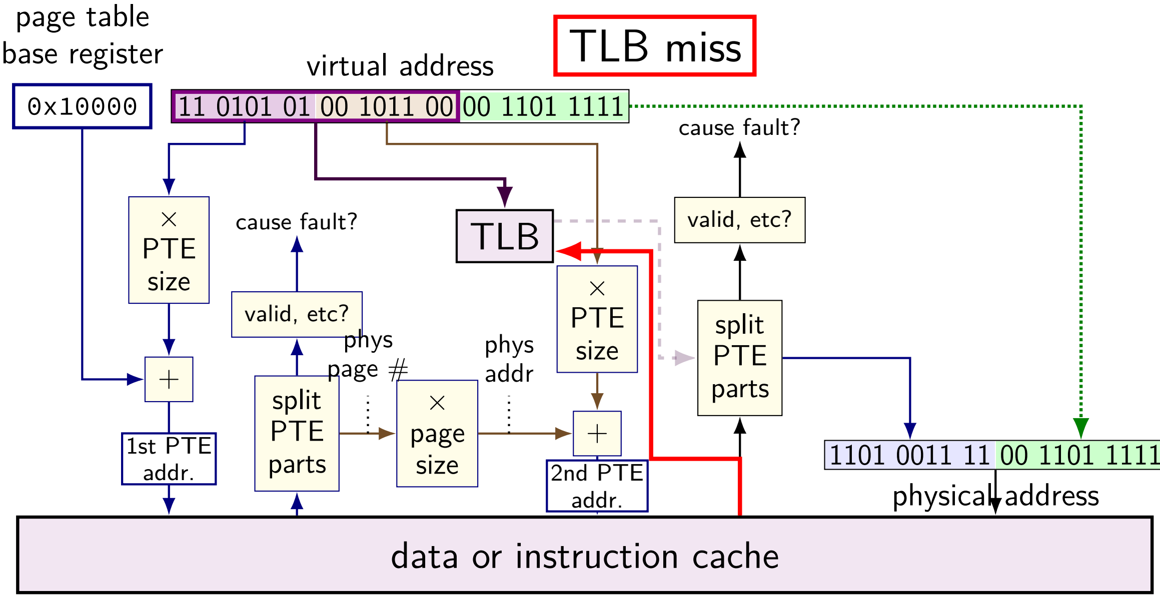
doesn't matter which last-level page table

means TLB output can be used directly to form address

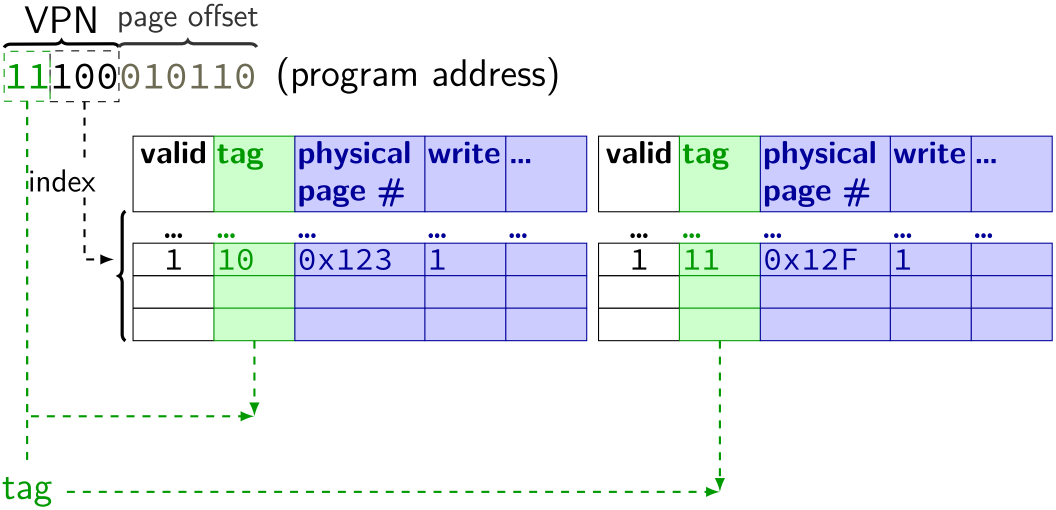
TLB and two-level lookup



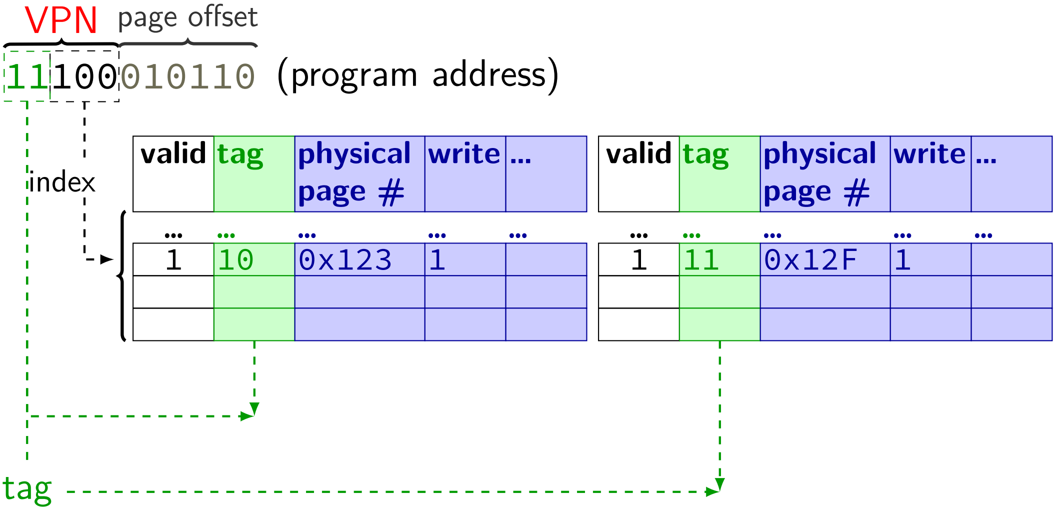
TLB and two-level lookup



TLB organization (2-way set associative)



TLB organization (2-way set associative)



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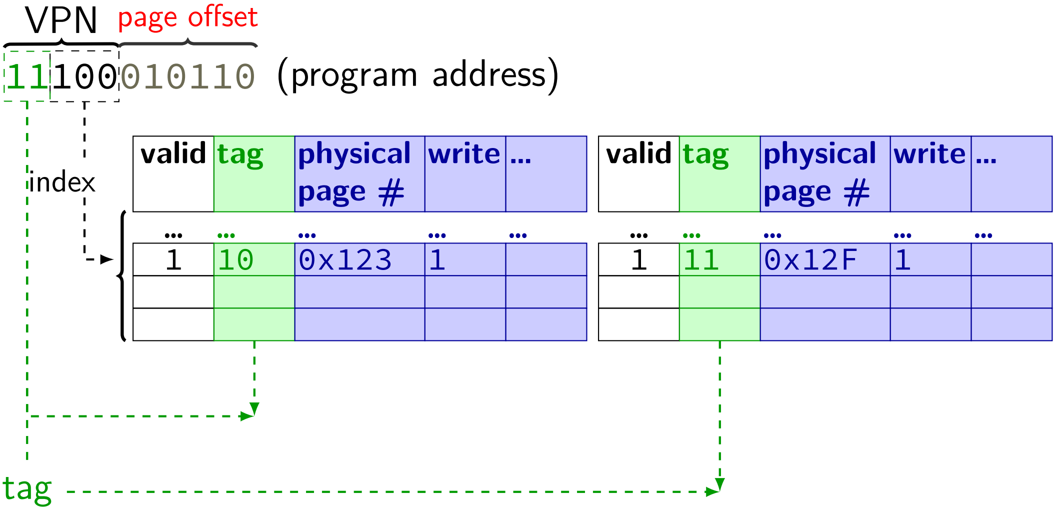

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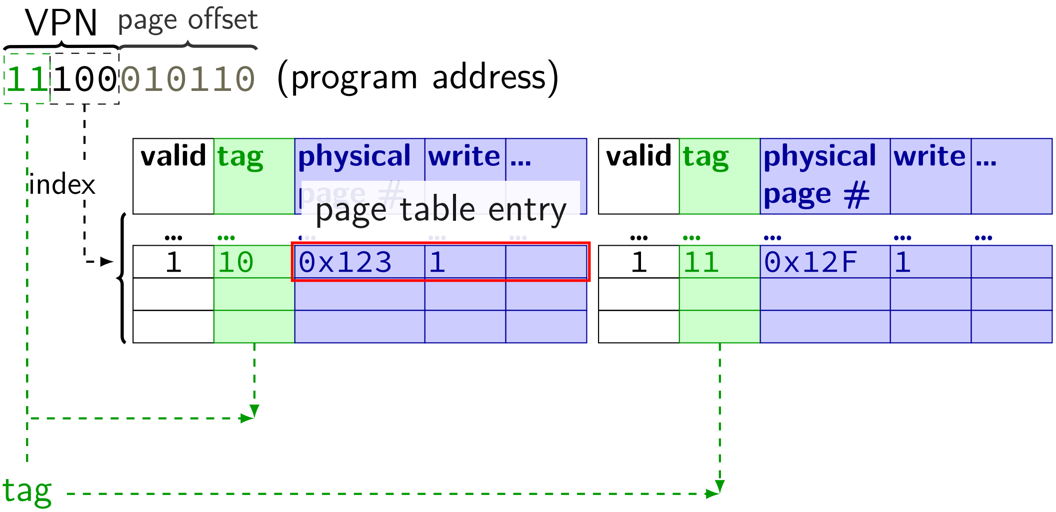
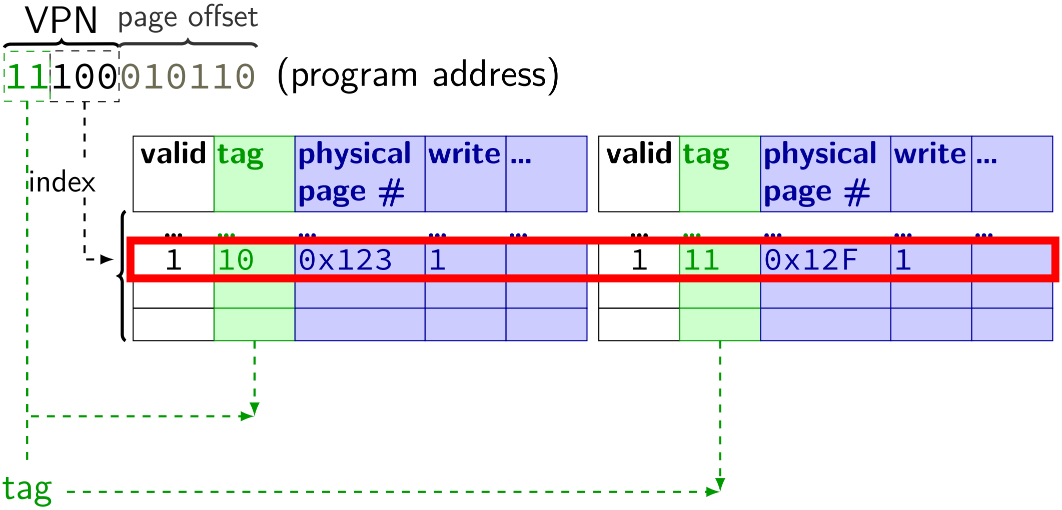


TLB organization (2-way set associative)



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?

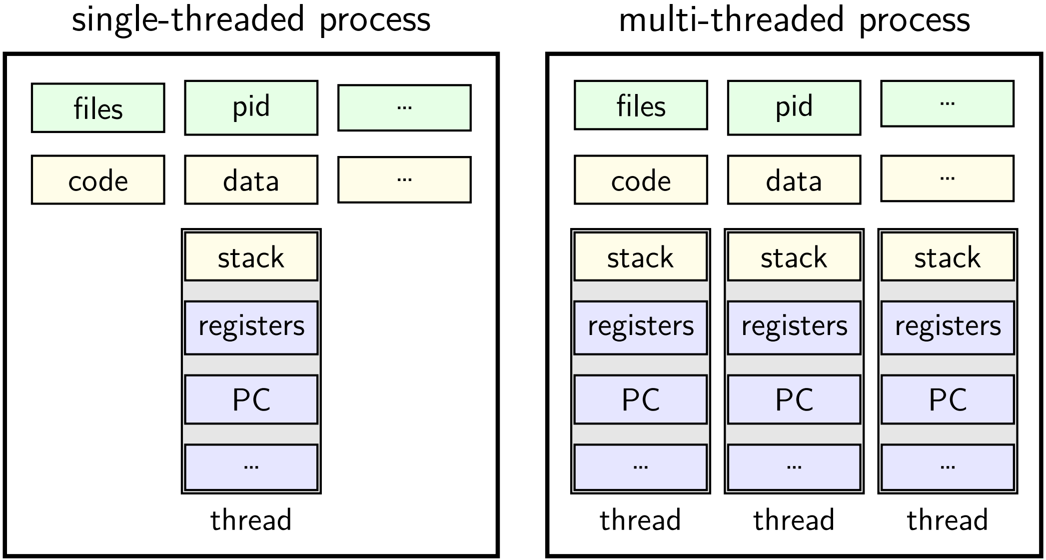
concurrency: different things happening at once

- 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

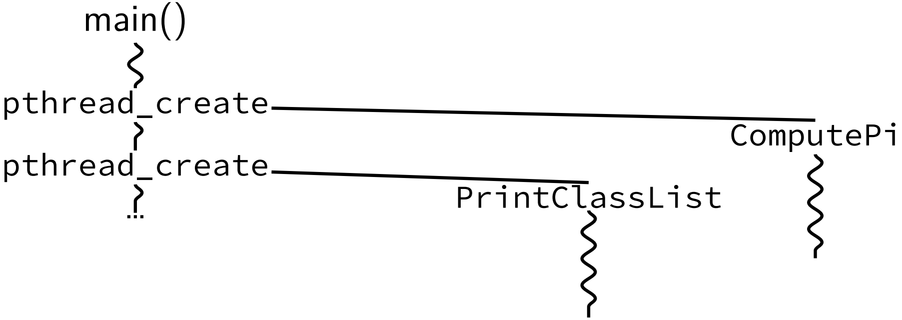
- multiple processors to speed-up simulation (life assignment)

single and multithread processes



pthread_create

```
void *ComputePi(void *argument) { ...  }
void *PrintClassList(void *argument) { ...  }
int main() {
    pthread_t pi_thread, list_thread;
    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

pthread_create

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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.

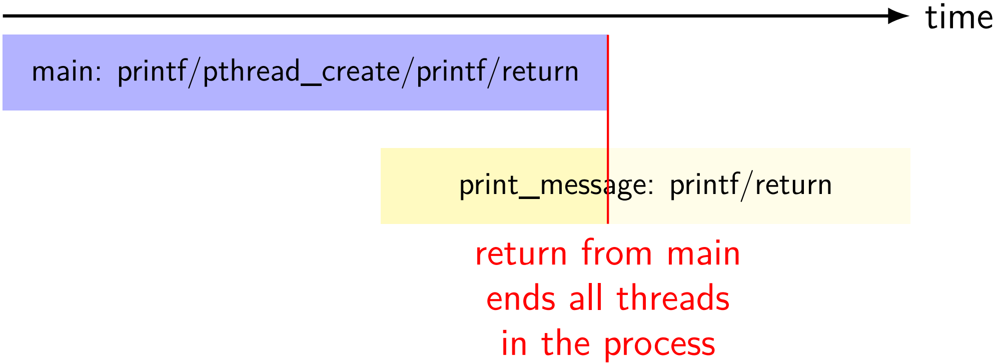
What happened?

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, retrieves its return value

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

`pthread_exit`: exit current thread, returning a value

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

sum example (only globals)

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

sum example (only globals)

values, results: global variables — shared

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

sum example (only globals)

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

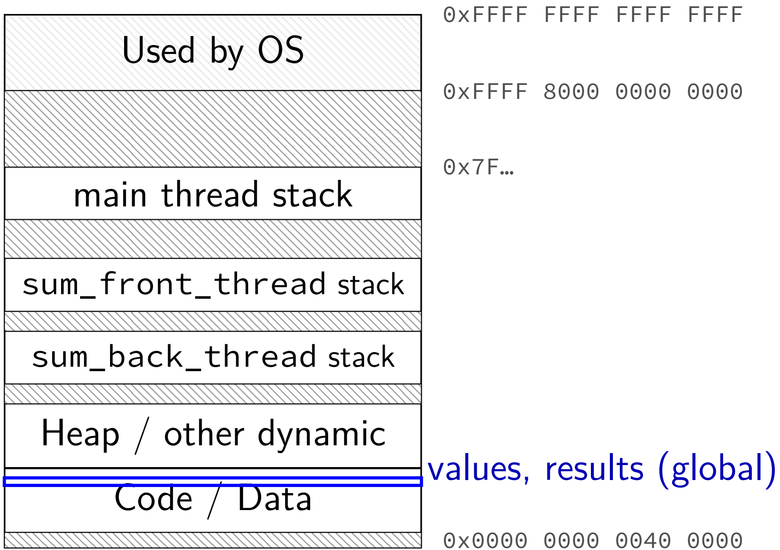
```
int values[1024];
int results[2];
void *sum_front(void *ignored_argument) {
    int sum = 0;
    for (int i = 0; i < 512; ++i) { sum += values[i]; }
    results[0] = sum;
    return NULL;
}
void *sum_back(void *ignored_argument) {
    int sum = 0;
    for (int i = 512; i < 1024; ++i) { sum += values[i];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

sum

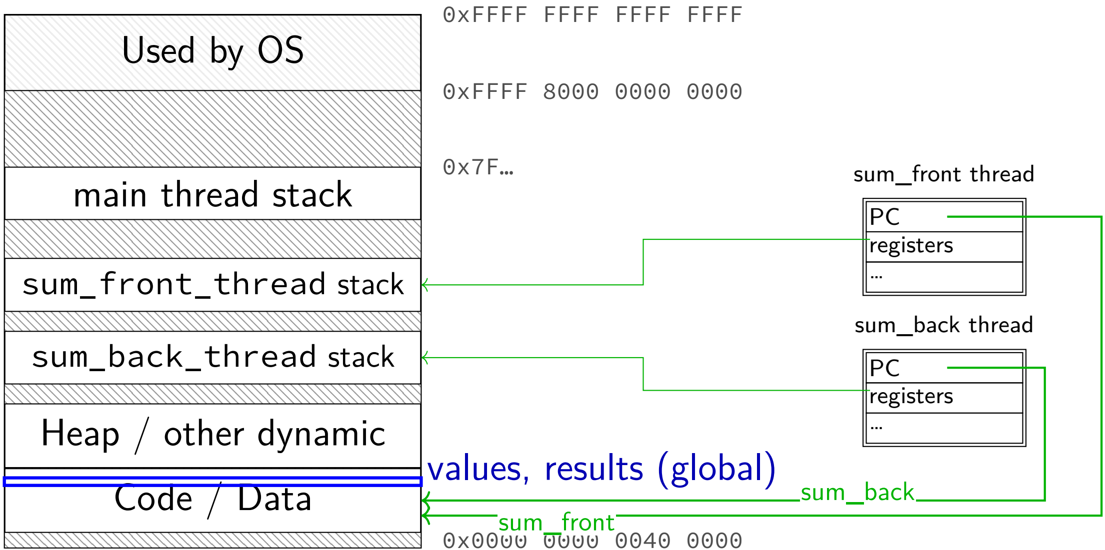
values returned from threads
via global array instead of return value
(partly to illustrate that memory is shared,
partly because this pattern works when we don't join (later))

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

thread_sum memory layout



thread_sum memory layout



sum example (to global, with thread IDs)

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

sum example (to global, with thread IDs)

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

values, results: global variables — shared

sum example (info struct)

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

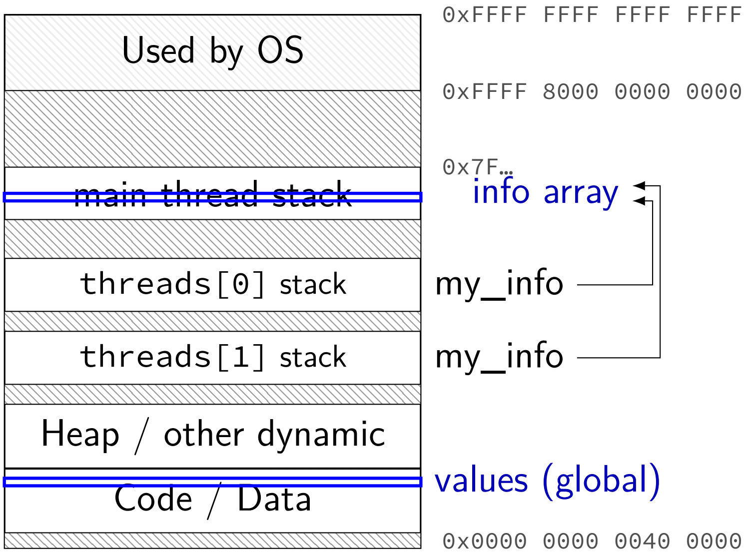
my_info: pointer to sum_all's stack

only okay because sum_all waits!

sum example (info struct)

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

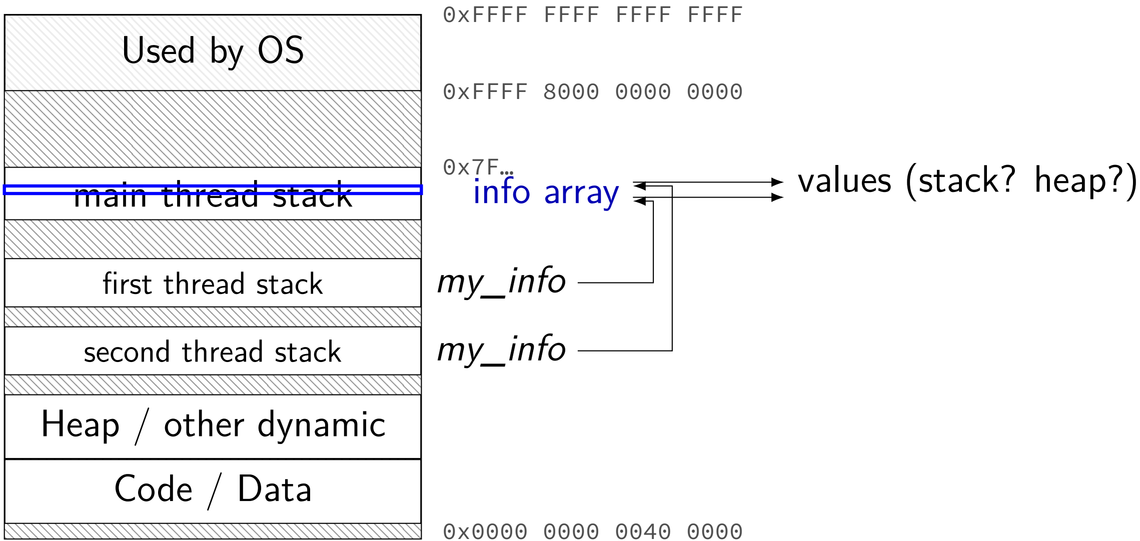
sum example (to main stack)

```
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;
}
```

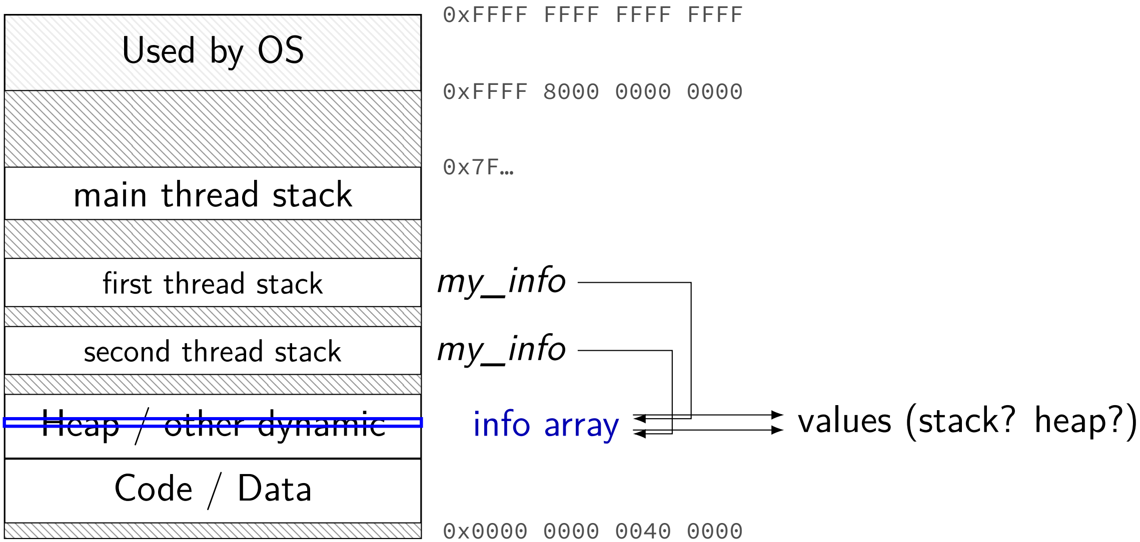
sum example (on heap)

```
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);
    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);
    int result = info[0].result + info[1].result;
    free(info);
    return result;
}
```

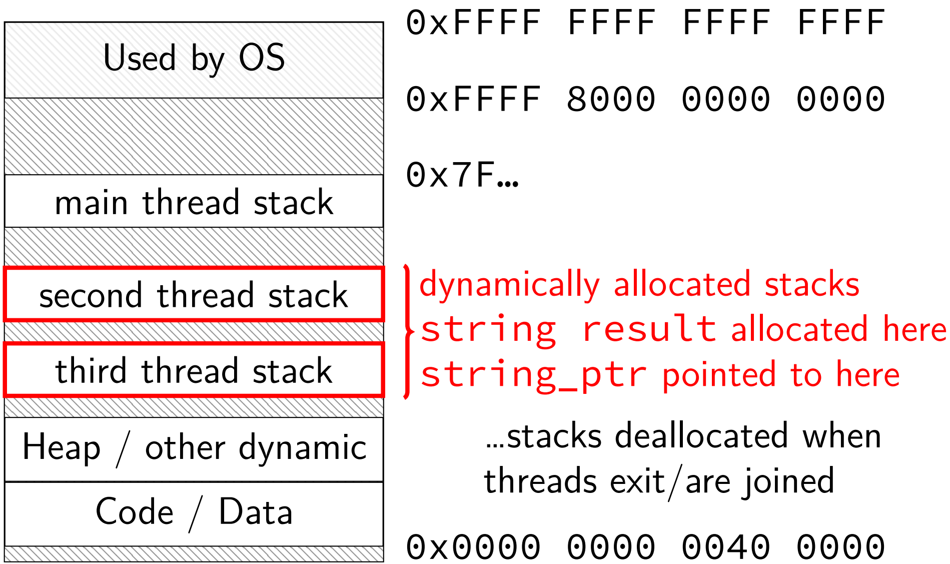
thread_sum memory (heap version)



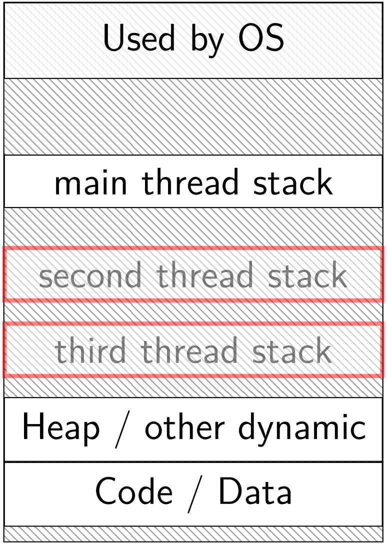
what's wrong with this?

```c
/* 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



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 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 note on error checking

from pthread_create manpage:

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

       EINVAL Invalid settings in attr.

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

special constants for *return value*

same pattern for many other pthreads functions

will often omit error checking in slides for brevity

error checking pthread_create

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

backup slides

cache miss types

common to categorize misses:

roughly "cause" of miss assuming cache block size fixed

compulsory (or *cold*) — first time accessing something

adding more sets or blocks/set wouldn't change

conflict — sets aren't big/flexible enough

a fully-assocititive (1-set) cache of the same size would have done better

capacity — cache was not big enough

coherence — from sync'ing cache with other caches

only issue with multiple cores

making any cache look bad

1. access enough blocks, to fill the cache
2. access an additional block, replacing something
3. access last block replaced
4. access last block replaced
5. access last block replaced

…

but — typical real programs have locality

cache optimizations

(assuming typical locality + keeping cache size constant if possible...)

	miss rate	hit time	miss penalty
increase cache size	better	worse	—
increase associativity	better	worse	worse?
increase block size	depends	worse	worse
add secondary cache	—	—	better
write-allocate	better	—	?
writeback	—	—	?
LRU replacement	better	?	worse?
prefetching	better	—	—

prefetching = guess what program will use, access in advance

$$\text{average time} = \text{hit time} + \text{miss rate} \times \text{miss penalty}$$

cache optimizations by miss type

(assuming other listed parameters remain constant)

	capacity	conflict	compulsory
increase cache size	fewer misses	fewer misses	—
increase associativity	—	fewer misses	—
increase block size	more misses?	more misses?	fewer misses
LRU replacement	—	fewer misses	—
prefetching	—	—	fewer misses

thread versus process state

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

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

process info with threads

parent process info

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

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

Linux idea: task_struct

Linux model: single "task" structure = thread

pointers to address space, open file list, etc.

pointers can be shared

- e.g. shared open files: open fd 4 in one task $\rightarrow$ 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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`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

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