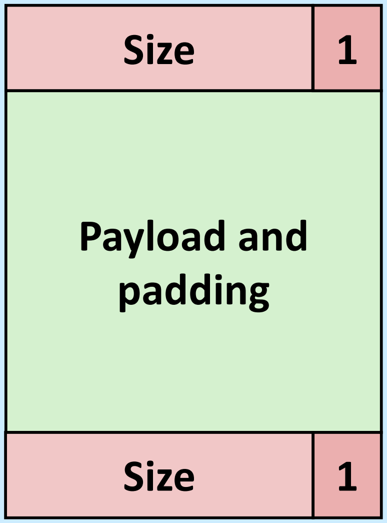
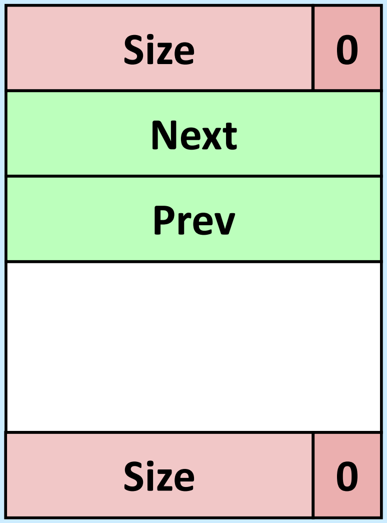
CS 33

C and Storage Allocation
Virtual Memory

C vs. Storage Allocation





```
typedef struct block {
  long size;
  long payload[size/8 - 2];
  long end_size;
} block_t;
```

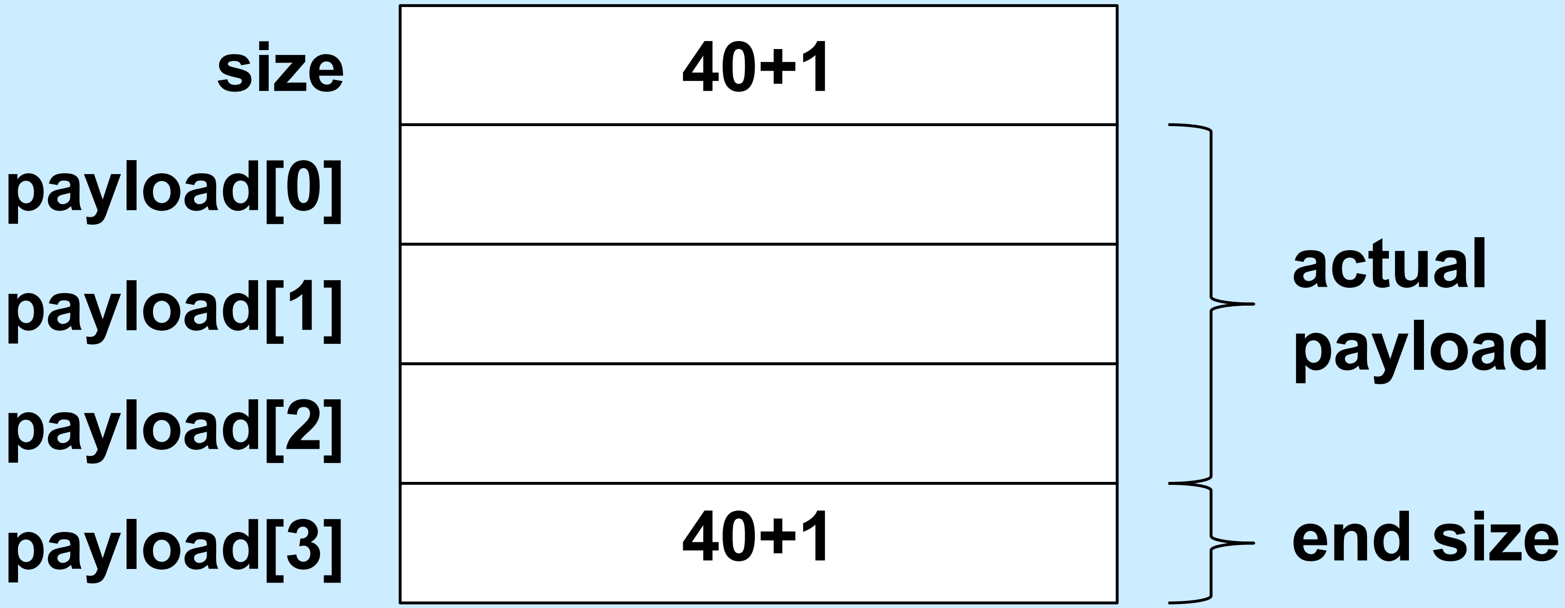
```
typedef struct free_block {
  long size;
  struct free_block *next;
  struct free_block *prev;
  long filler[size/8 - 4];
  long end_size;
} free_block_t;
```

Overcoming C

- Think objects
  - a block is an object
    - » opaque to the outside world
  - define accessor functions to get and set its contents

```
typedef struct block {
   size_t size;
   size_t payload[0];
} block_t;
```

Allocated Block



size

40+1

payload[0]

payload[1]

payload[2]

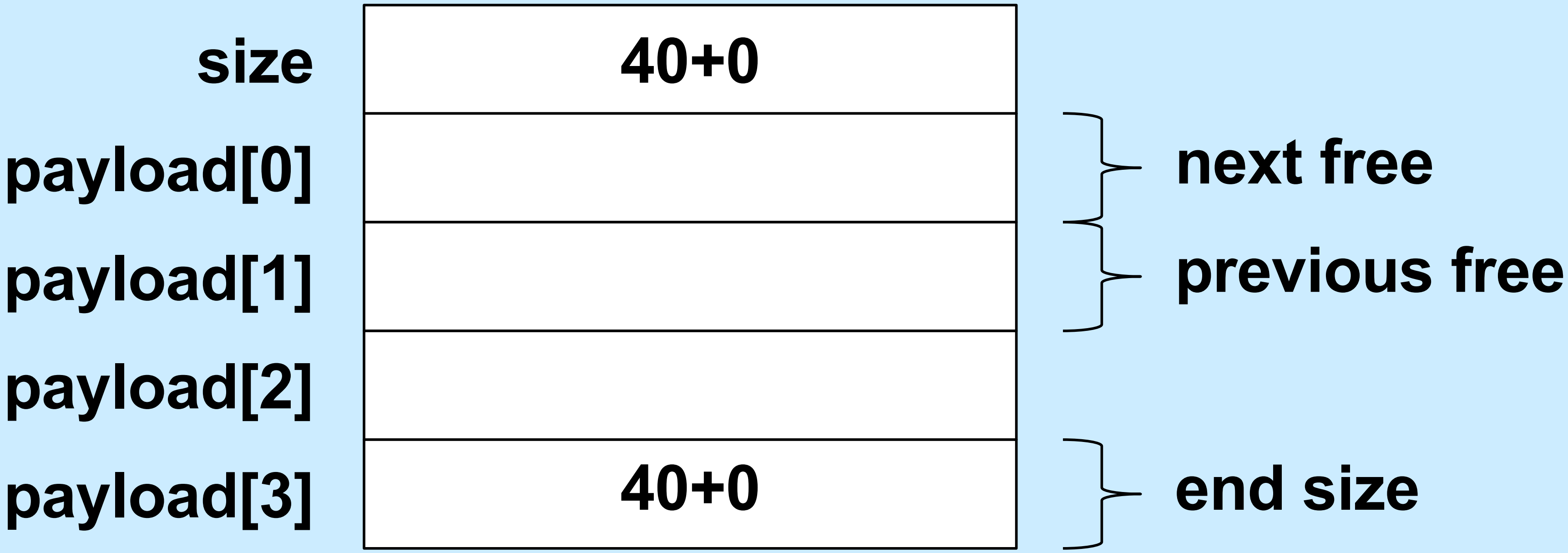
payload[3]

40+1

actual payload

end size

Free Block



size 40+0

payload[0]

payload[1]

payload[2]

payload[3] 40+0

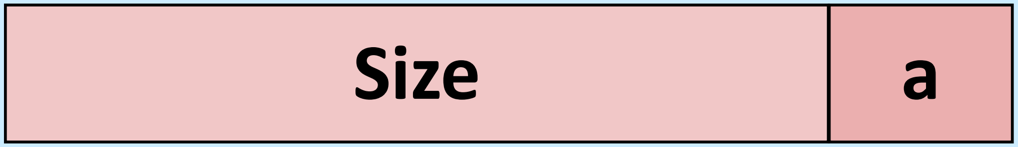
next free

previous free

end size

- In general, end size is at *payload[size/8 – 2]*

Overloading Size

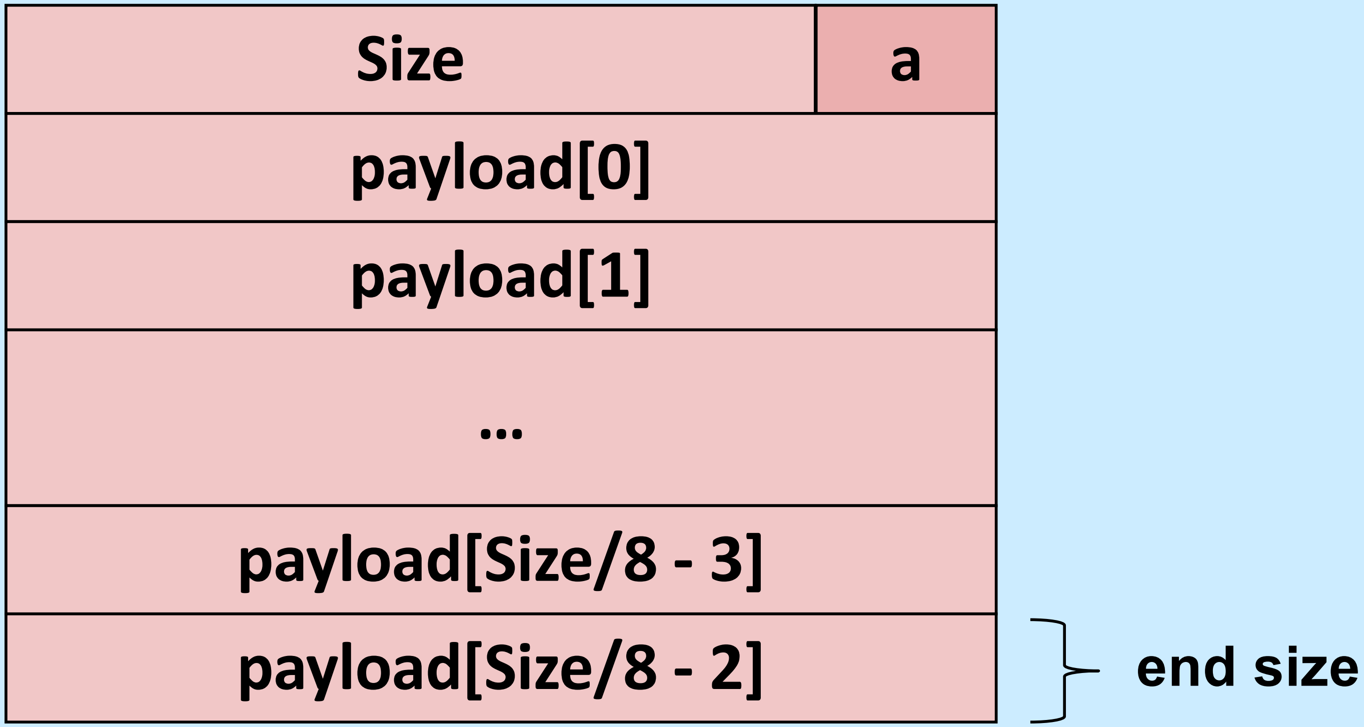


Size

a

```
size_t block_allocated(block_t *b) {
  return b->size & 1;
}

size_t block_size(block_t *b) {
  return b->size & -2;
}
```

End Size



Size | a

payload[0]

payload[1]

...

payload[Size/8 - 3]

payload[Size/8 - 2]

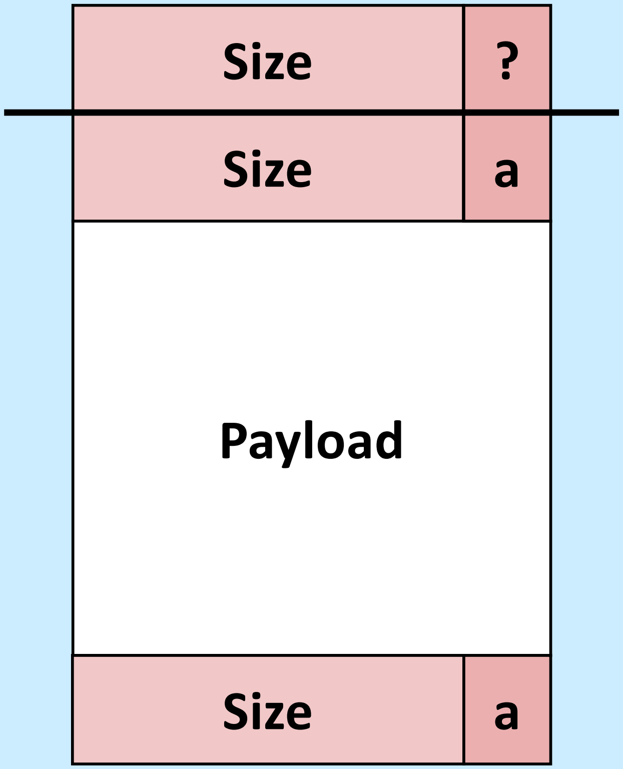
end size

```
size_t *block_end_tag(block_t *b) {
  return &b->payload[b->size/8 - 2];
}
```

Setting the Size

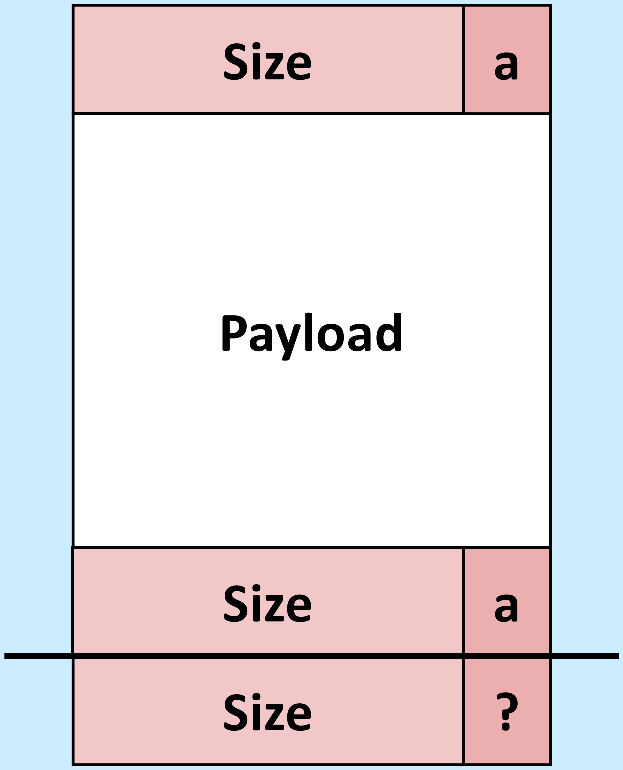
```
void block_setsize(block_t *b, size_t size) {
  assert(!(size & 7));         // multiple of 8
  size |= block_allocated(b);  // preserve alloc bit
  b->size = size;
  *block_end_tag(b) = size;
}

void block_set_allocated(block_t *b, size_t a) {
  assert((a == 0) || (a == 1));
  if (a) {
    b->size |= 1;
    *block_end_tag(b) |= 1;
  } else {
    b->size &= -2;
    *block_end_tag(b) &= -2;
  }
}
```

Is Previous Adjacent Block Free?



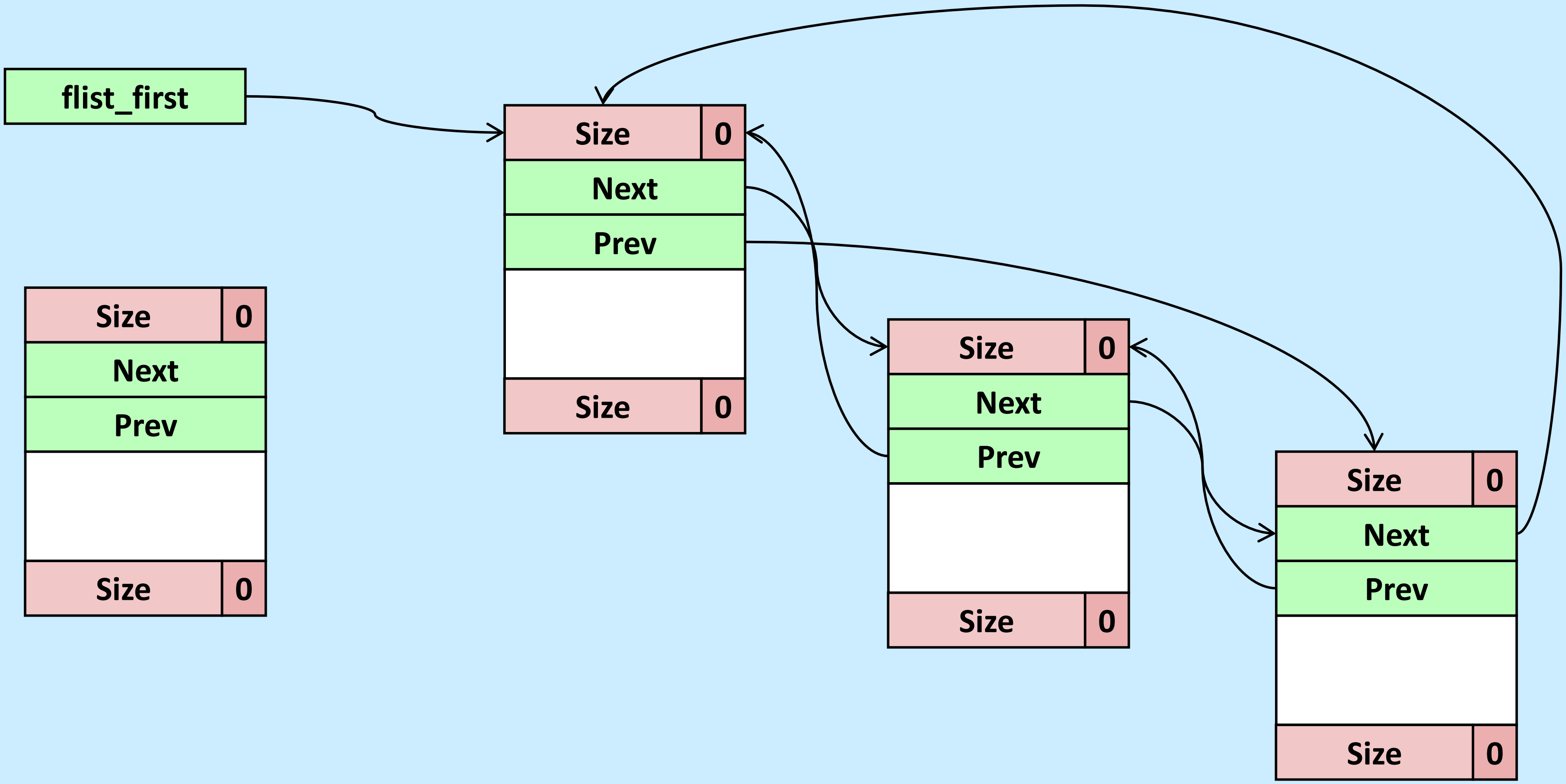
```
size_t block_prev_allocated(
    block_t *b) {
  return b->payload[-2] & 1;
}
```

Is Next Adjacent Block Free?

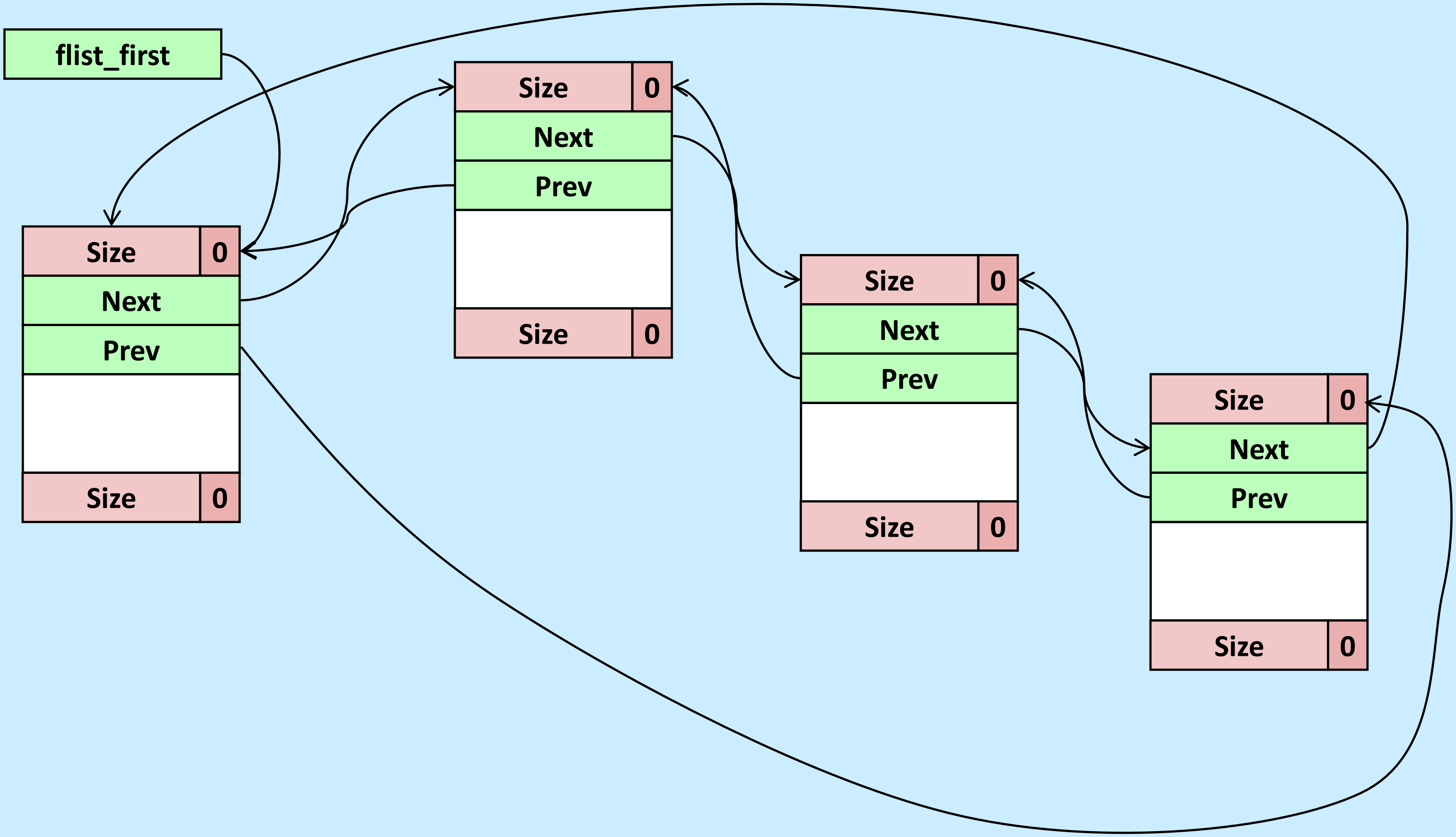


```
block_t *block_next(
    block_t *b) {
  return (block_t *)
    ((char *)b + block_size(b));
}

size_t block_next_allocated(
    block_t *b) {
  return block_allocated(
    block_next(b));
}
```

Adding a Block to the Free List (1)



Adding a Block to the Free List (2)



Accessing the Object

```
block_t *block_next_free(block_t *b) {
  return (block_t *)b->payload[0];
}

void block_set_next_free(block_t *b, block_t *next) {
  b->payload[0] = (size_t)next;
}

block_t *block_prev_free(block_t *b) {
  return (block_t *)b->payload[1];
}

void block_set_prev_free(block_t *b, block_t *next) {
  b->payload[1] = (size_t)next;
}
```

Insertion Code

```
void insert_free_block(block_t *fb) {
  assert(!block_allocated(fb));
  if (flist_first != NULL) {
    block_t *last =
      block_prev_free(flist_first);
    block_set_next_free(fb, flist_first);
    block_set_prev_free(fb, last);
    block_set_next_free(last, fb);
    block_set_prev_free(flist_first, fb);
  } else {
    block_set_next_free(fb, fb);
    block_set_prev_free(fb, fb);
  }
  flist_first = fb;
}
```

Performance

- Won’t all the calls to the accessor functions slow things down a lot?
  - yes — not just a lot, but tons
- Why not use macros (#define) instead?
  - the textbook does this
  - it makes the code impossible to debug
    - » gdb shows only the name of the macro, not its body
- What to do????

Inline functions

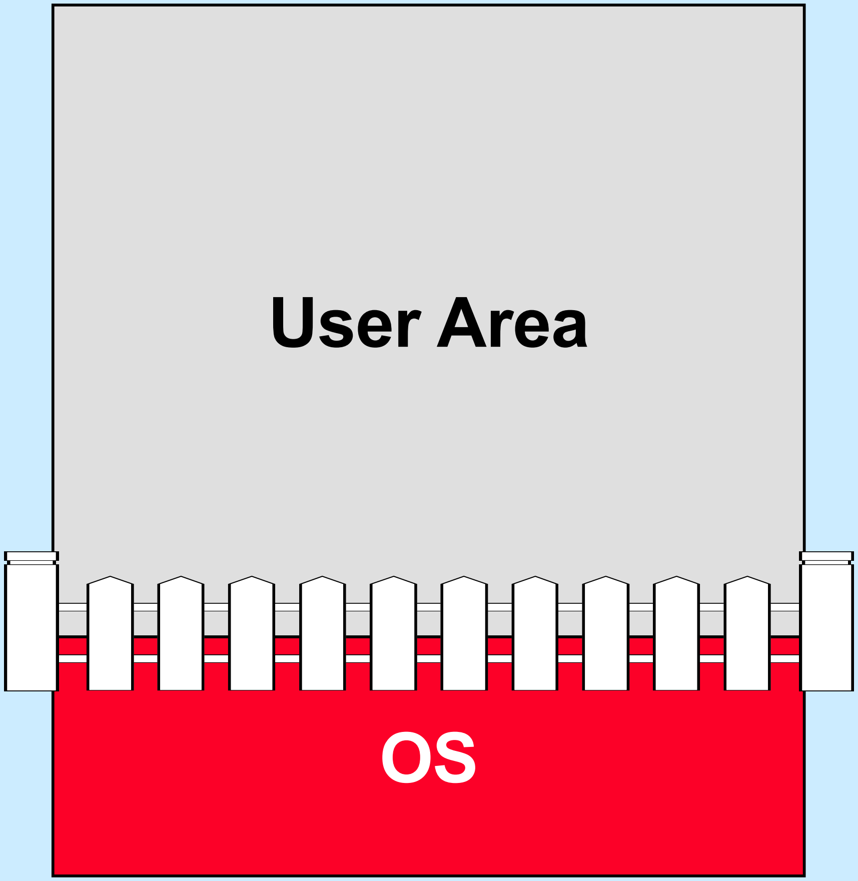
```
static inline size_t block_size(
      block_t *b) {
   return b->size & -2;
}
```

- when debugging (–O0), the code is implemented as a normal function
  - easy to debug with gdb
- when optimized (–O1, –O2), calls to the function are replaced with the body of the function
  - no function-call overhead

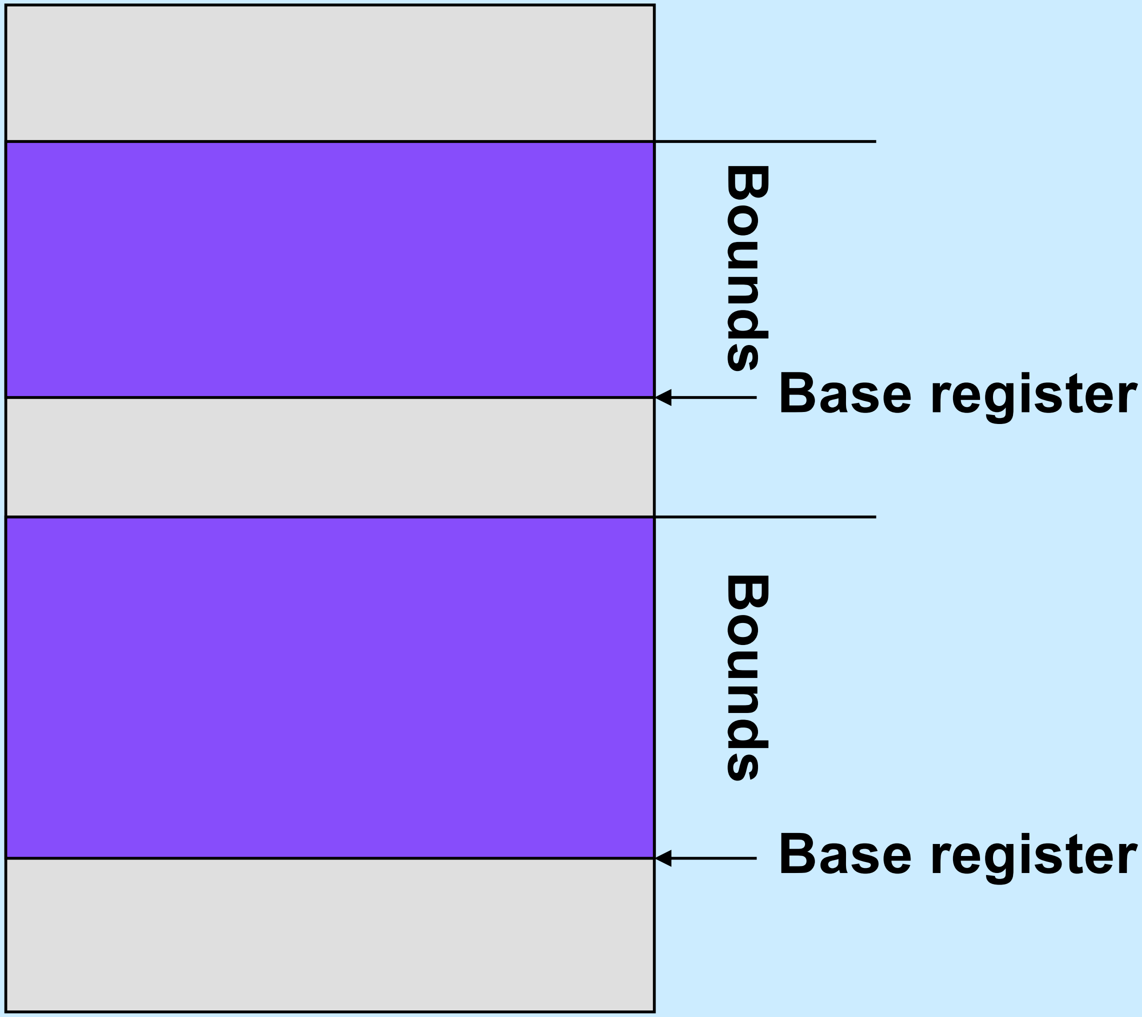
The Address-Space Concept

- Protect processes from one another
- Protect the OS from user processes
- Provide efficient management of available storage

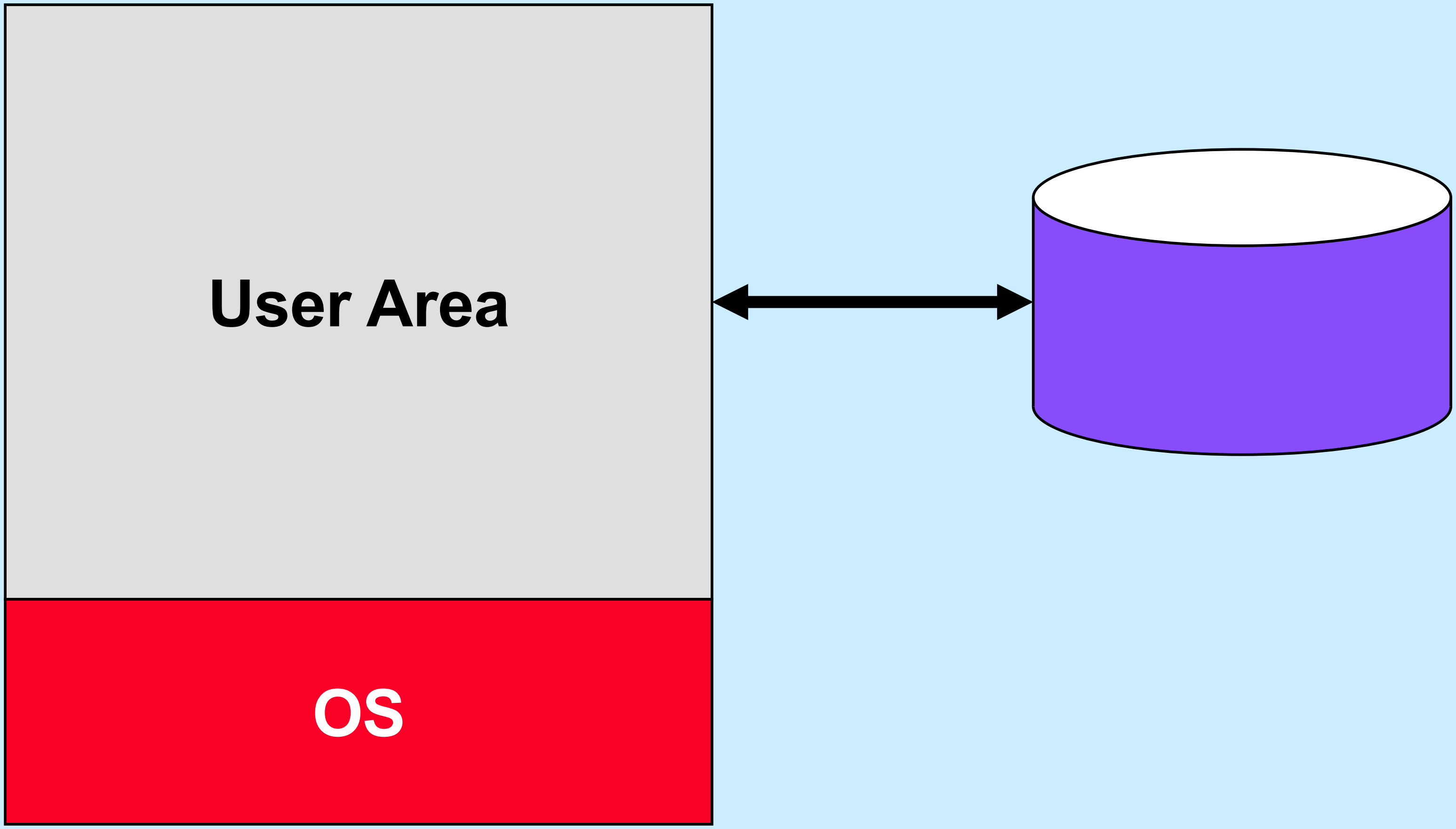
Memory Fence



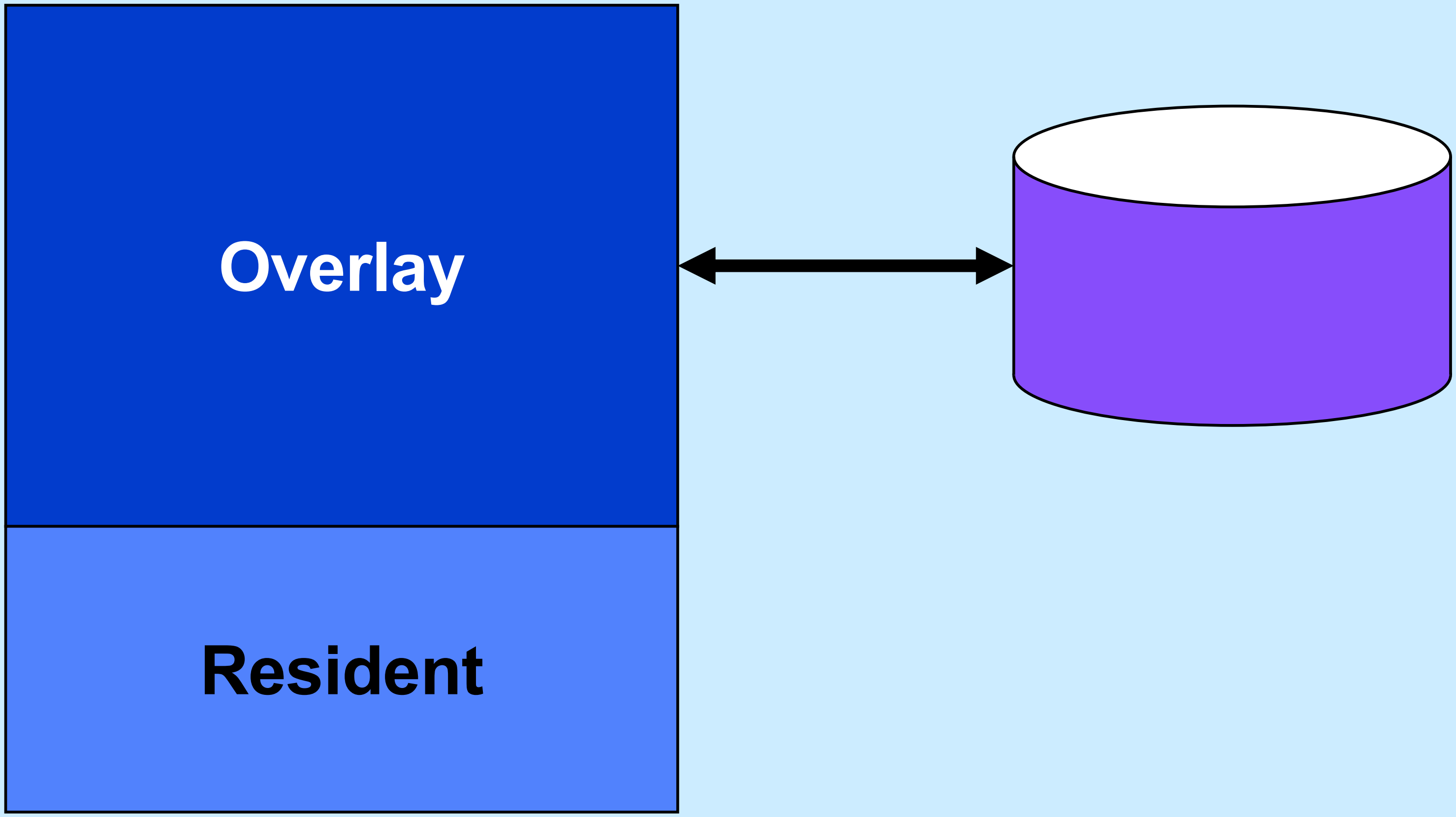
Base and Bounds Registers



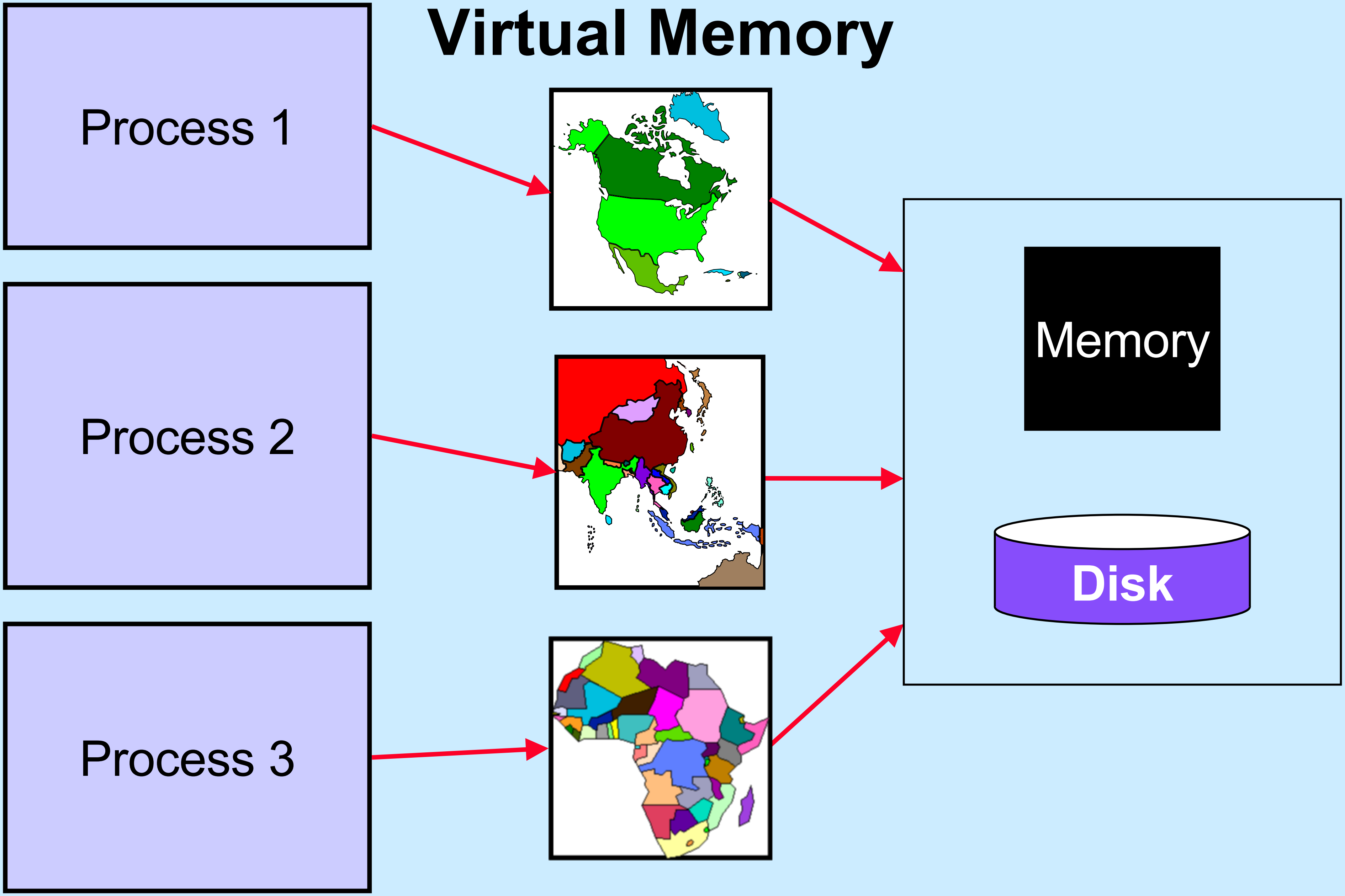
Swapping



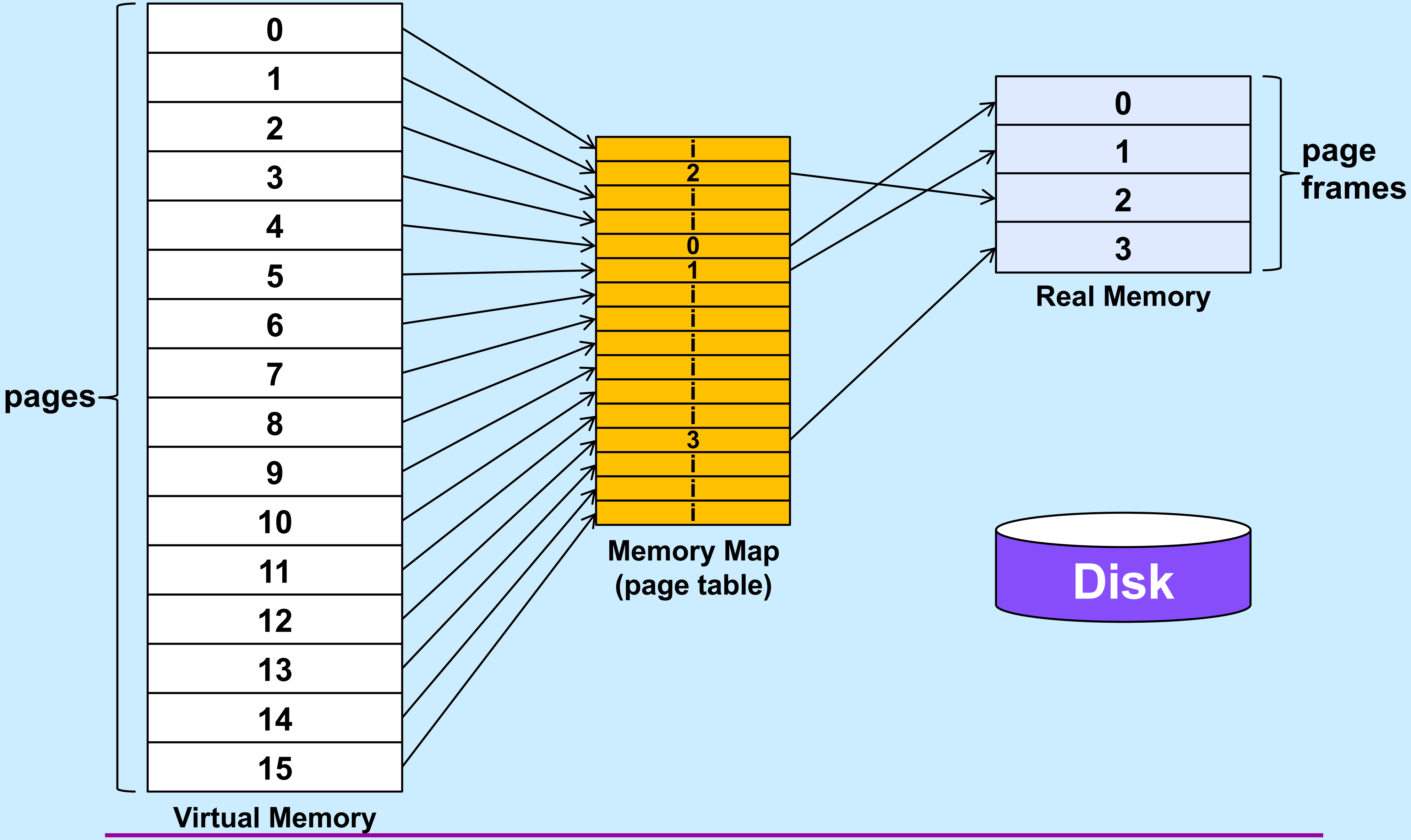
Overlays



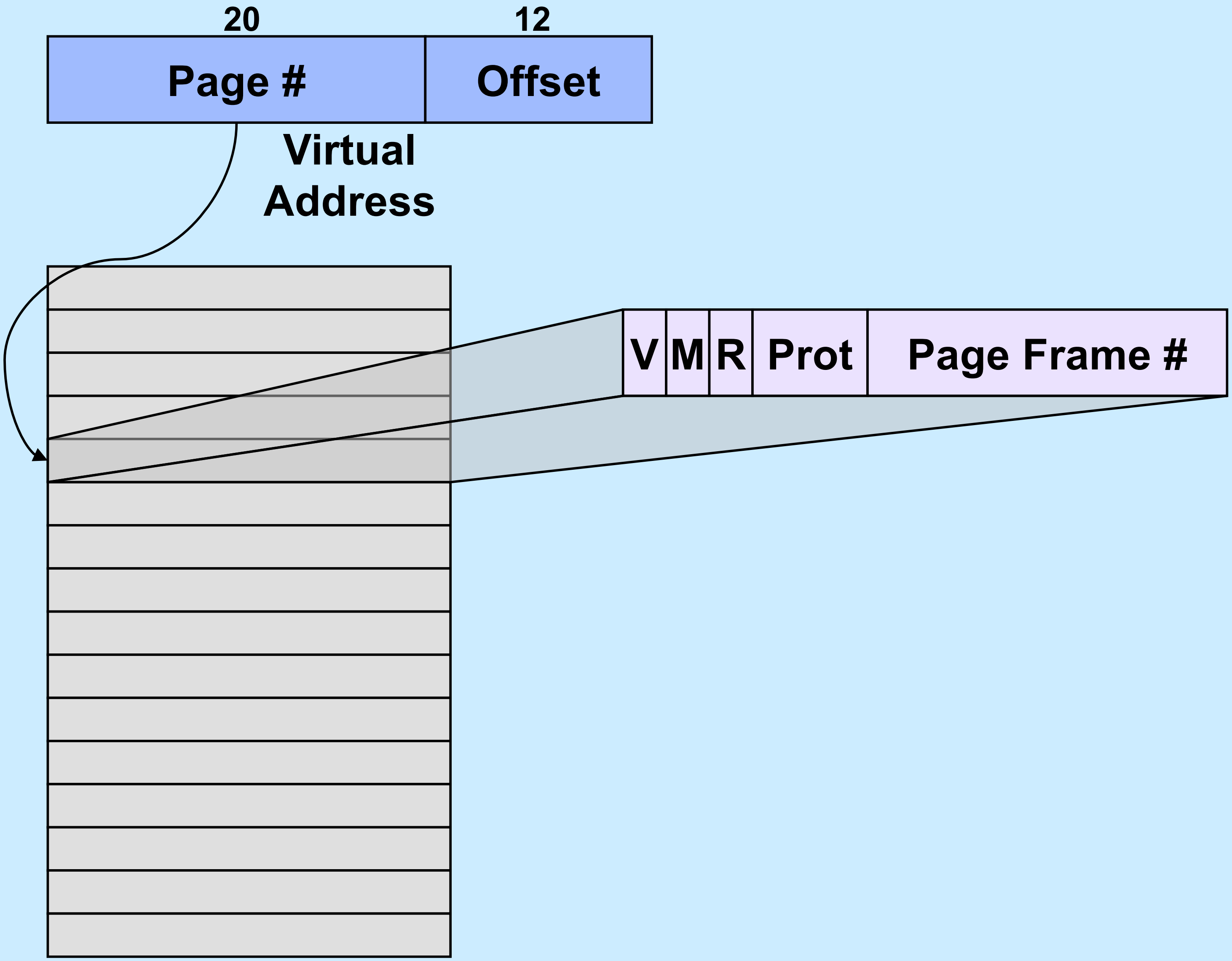
Virtual Memory



Memory Maps


pages
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
Virtual Memory
i
2
i
i
0
1
i
i
i
i
i
i
3
i
i
i
Memory Map
(page table)
0
1
2
3
page
frames
Real Memory
Disk

Page Tables



Quiz 1

How many 2^{12}-byte pages fit in a 32-bit address space?

a) a little over a 1000

b) a little over a million

c) a little over a billion

d) none of the above

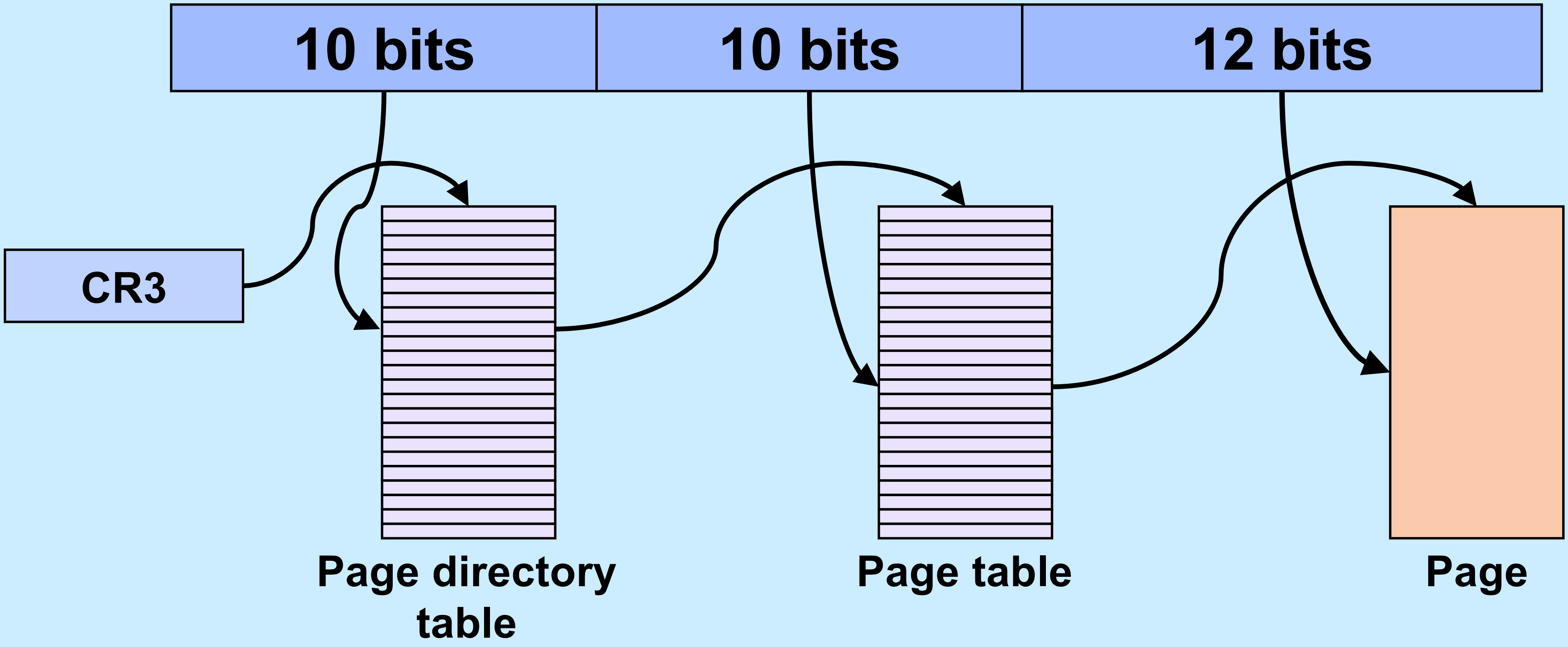
VM is Your Friend ...

- Not everything has to be in memory at once
  - pages brought in (and pushed out) when needed
  - unallocated parts of the address space consume no memory
    - » e.g., hole between stack and dynamic areas
- What's mine is not yours (and vice versa)
  - address spaces are disjoint
- Sharing is ok though ...
  - address spaces don't have to be disjoint
    - » a single page frame may be mapped into multiple processes
- I don't trust you (or me)
  - access to individual pages can be restricted
    - » read, write, execute, or any combination

Page-Table Size

- Consider a full 2^{32}-byte address space
  - assume 4096-byte (2^{12}-byte) pages
  - 4 bytes per page-table entry
  - the page table would consist of $2^{32}/2^{12}$ (= 2^{20}) entries
  - its size would be 2^{22} bytes (or 4 megabytes)
    - » at $100/gigabyte
      - around $0.40
- For a 2^{64}-byte address space
  - assume 4096-byte (2^{12}-byte) pages
  - 8 bytes per page-table entry
  - the page table would consist of $2^{64}/2^{12}$ (= 2^{52}) entries
  - its size would be 2^{55} bytes (or 32 petabytes)
    - » at $1/gigabyte
      - over $33 million

IA32 Paging


10 bits
10 bits
12 bits
CR3
Page directory table
Page table
Page

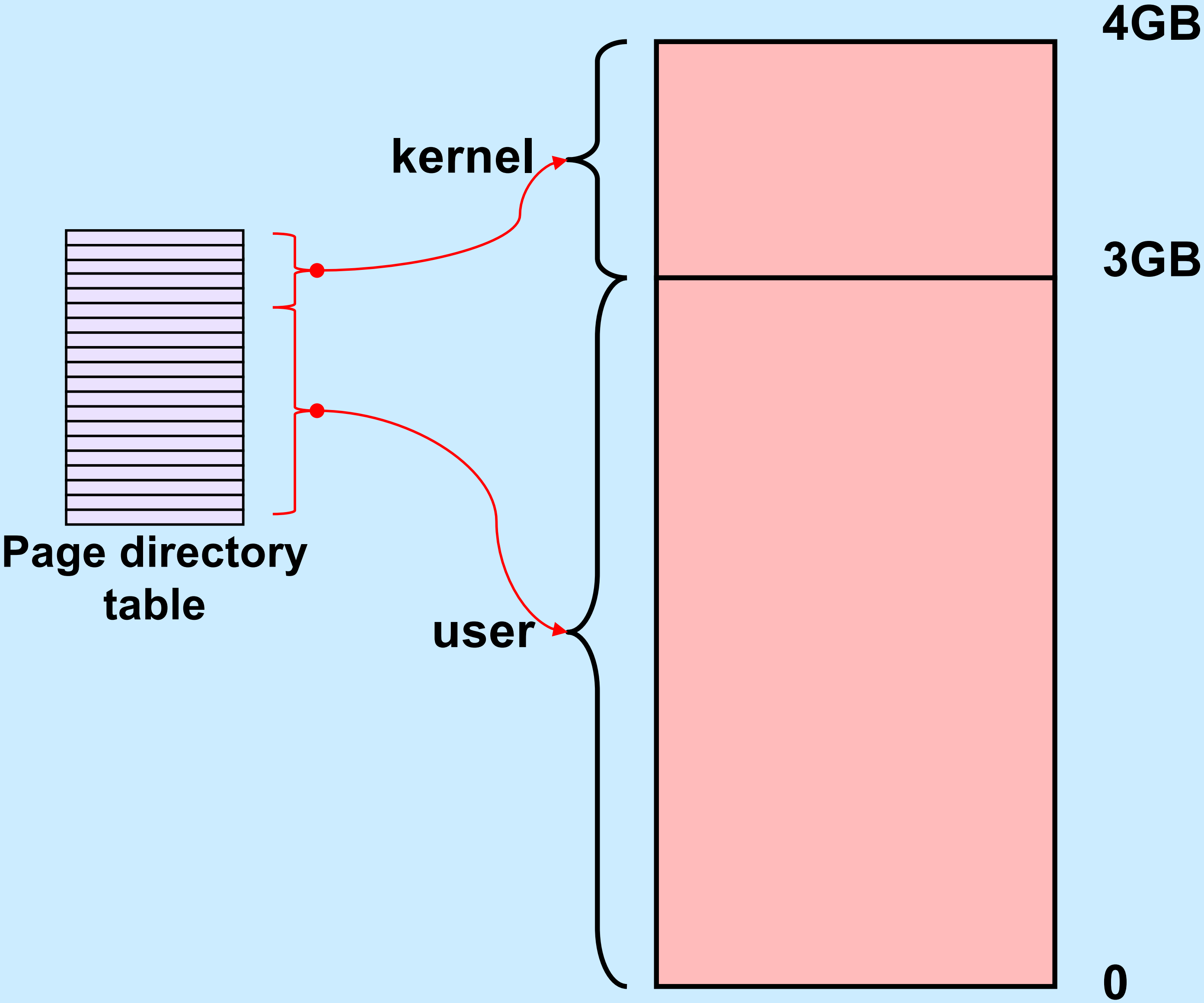
Quiz 2

Can a page start at a virtual address that's not divisible by the page size?

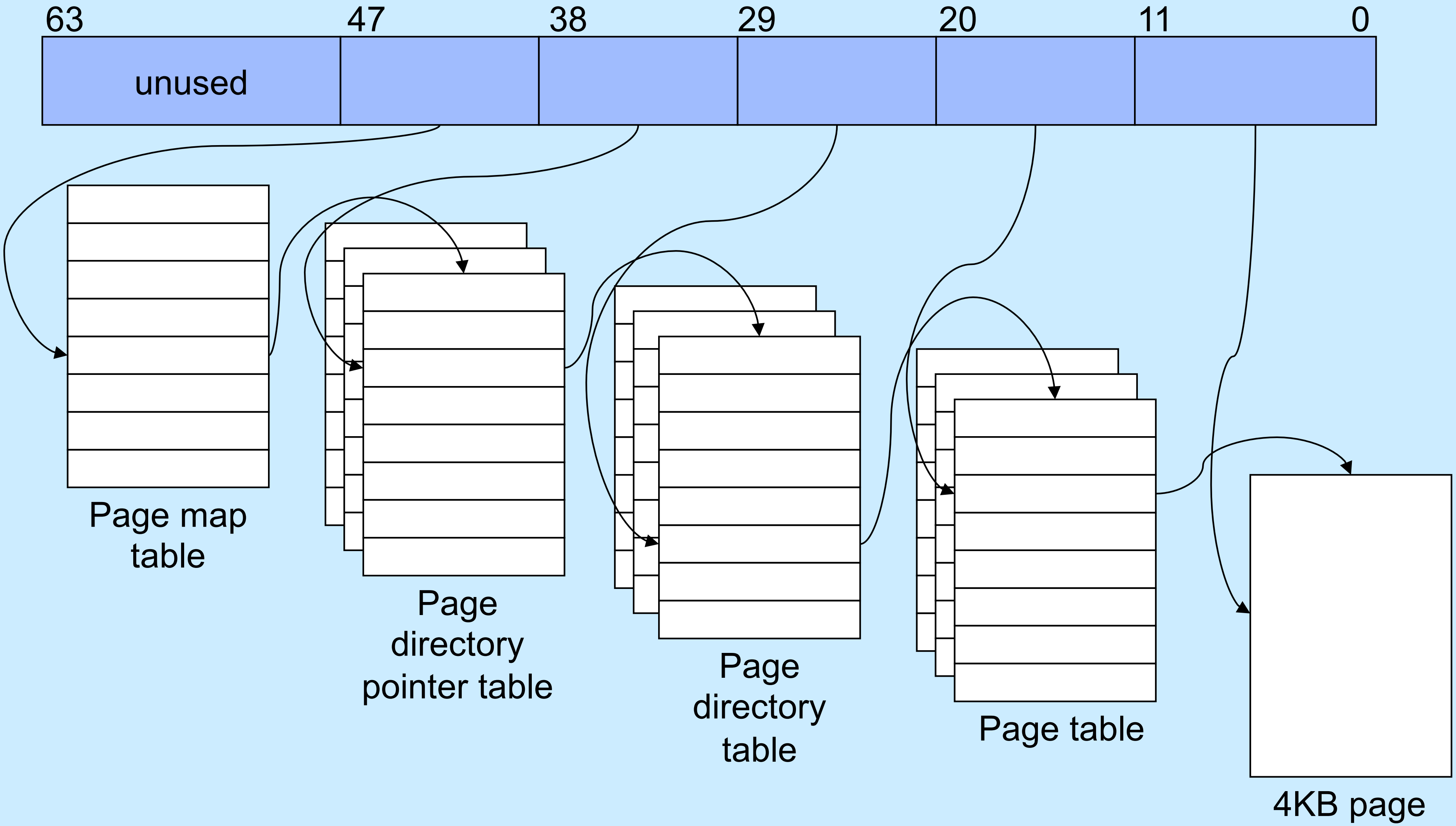
a) yes

b) no

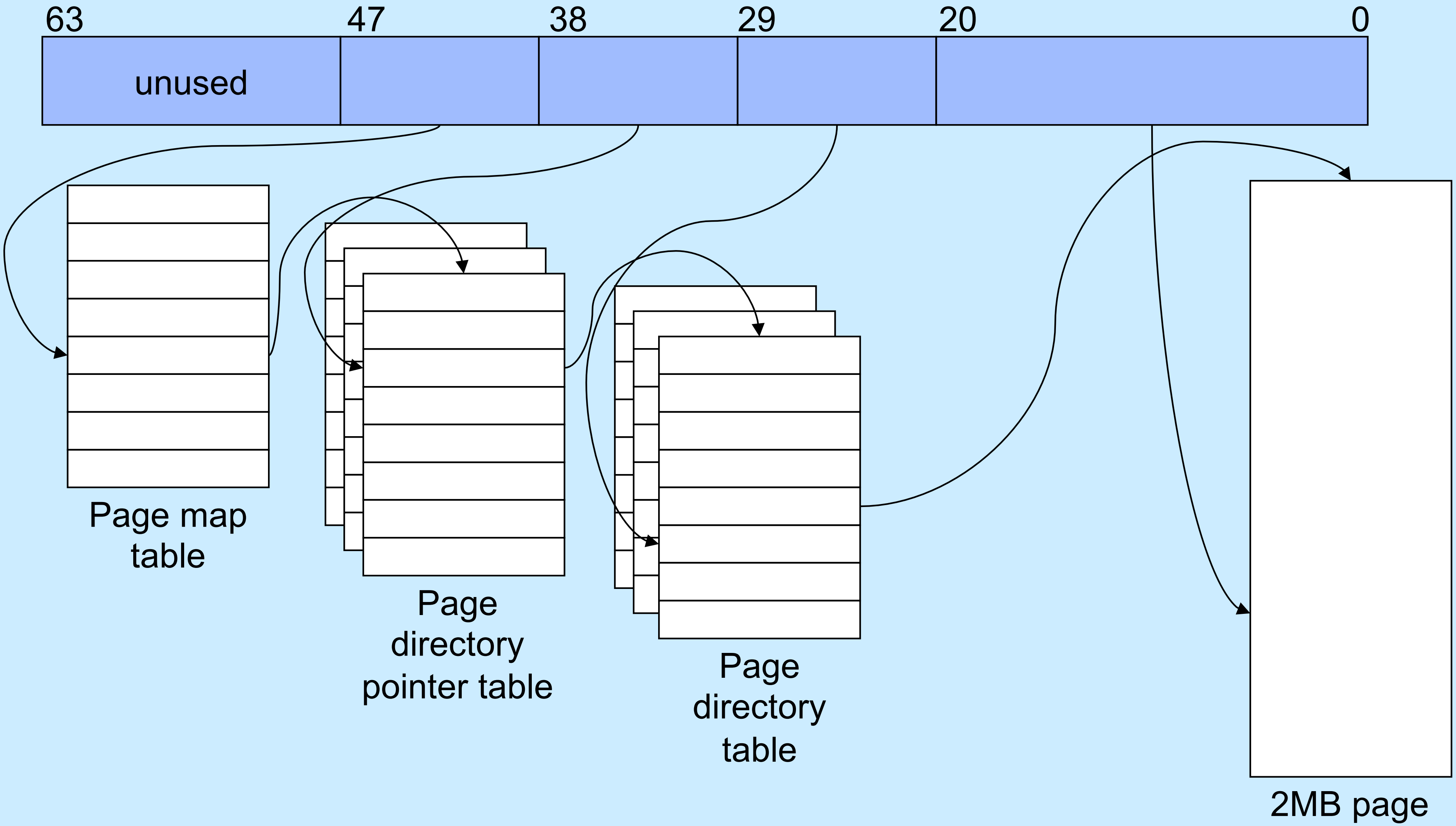
Linux Intel IA32 VM Layout



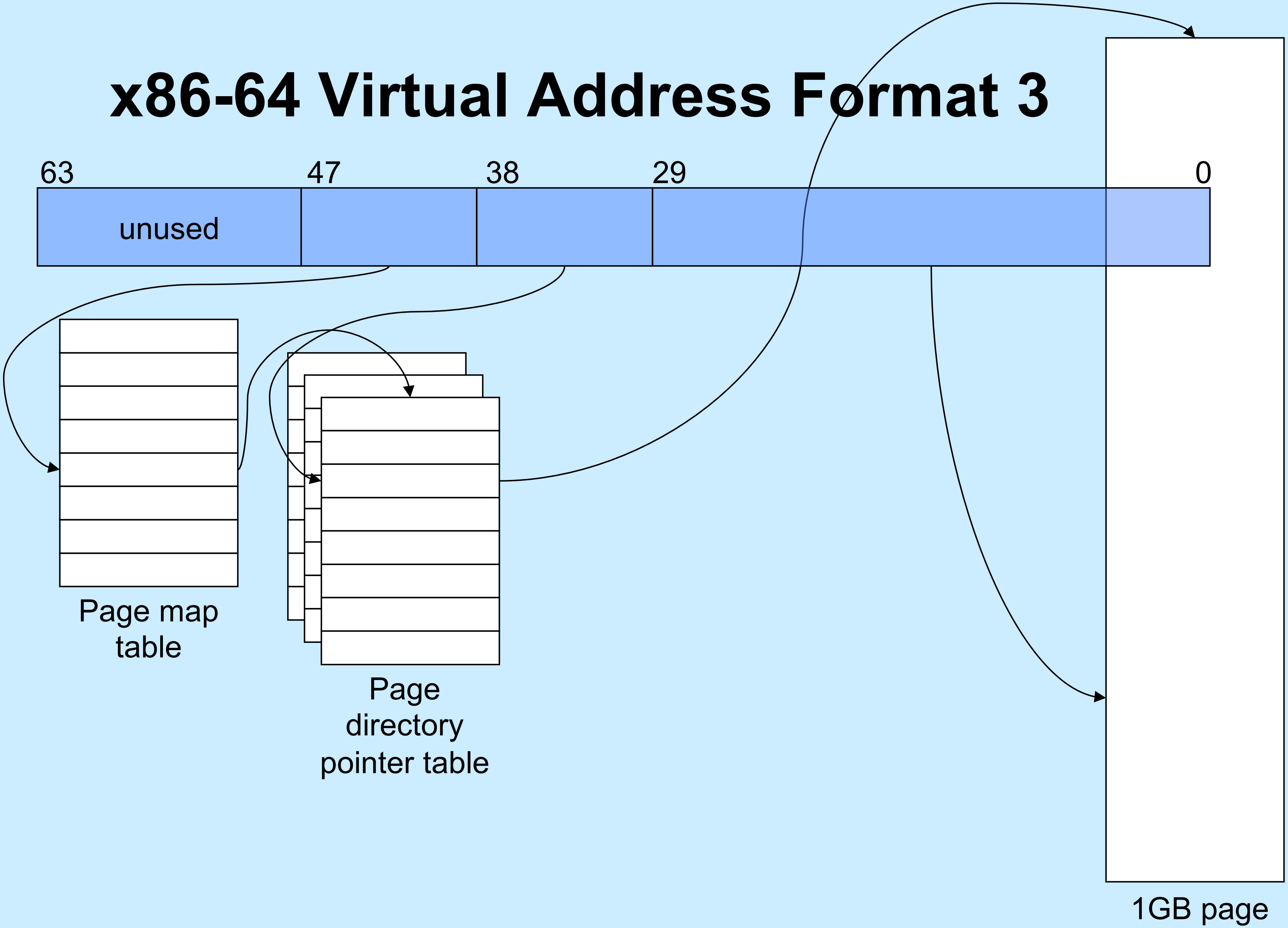
x86-64 Virtual Address Format 1



x86-64 Virtual Address Format 2



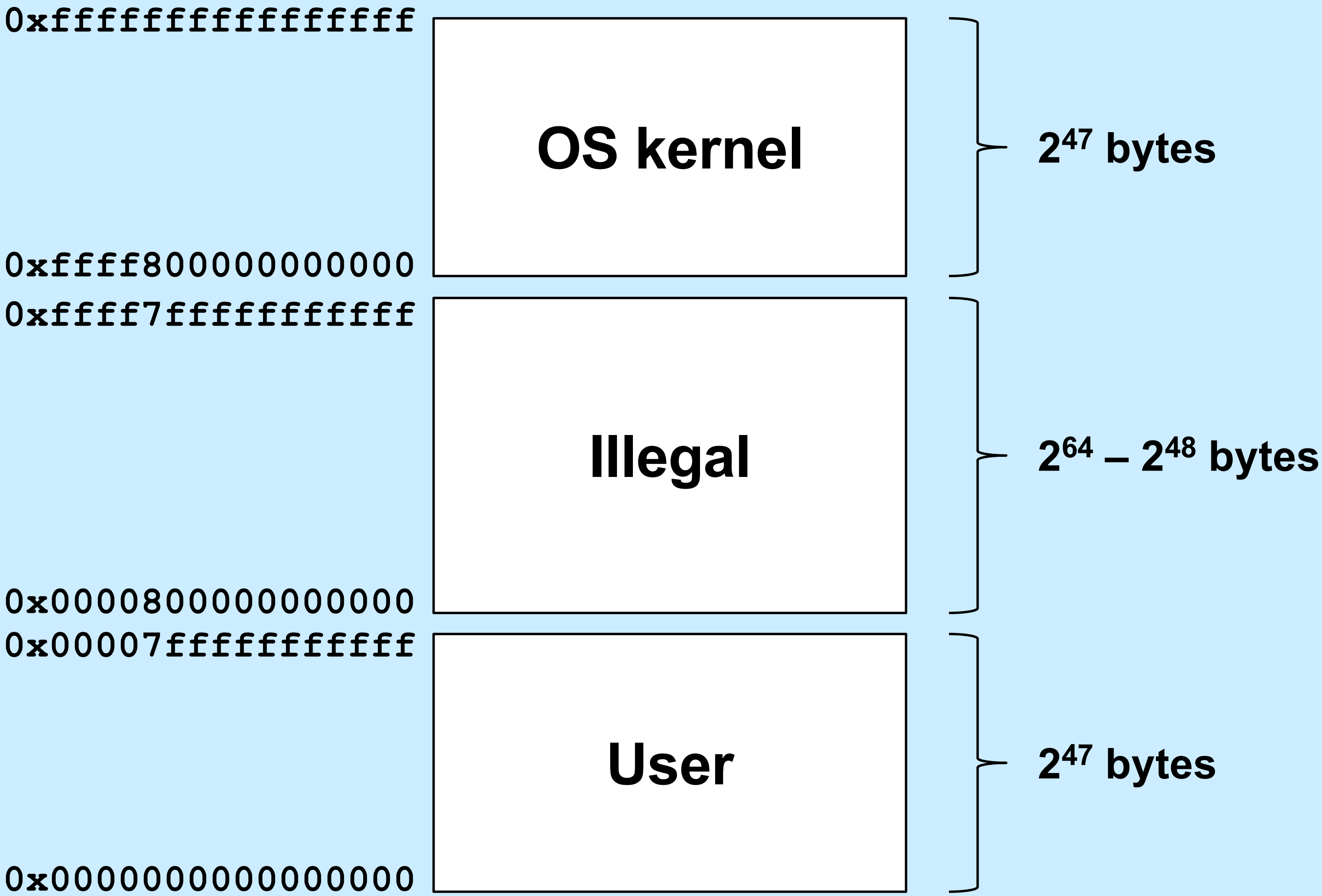
x86-64 Virtual Address Format 3



Why Multiple Page Sizes?

- Fragmentation
  - for region composed of 4KB pages, average internal fragmentation is 2KB
  - for region composed of 1GB pages, average internal fragmentation is 512MB
- Page-table overhead
  - larger page sizes have fewer page tables
    - less overhead in representing mappings

x86-64 Address Space



0xffffffffffffffff

OS kernel

2^{47} bytes

0xffff800000000000

0xffff7fffffffffff

Illegal

$2^{64} – 2^{48}$ bytes

0x0000800000000000

0x00007fffffffffff

User

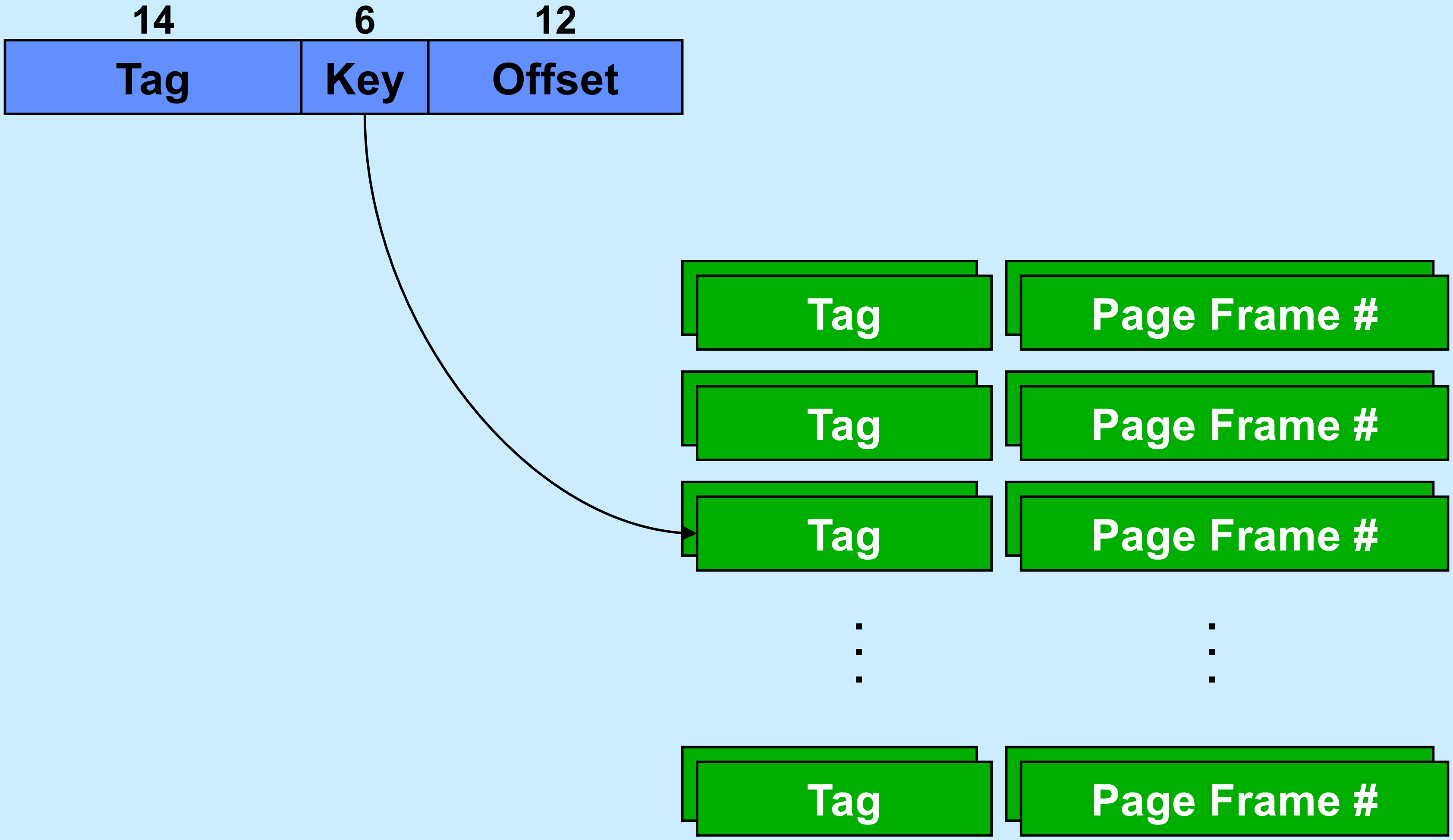
2^{47} bytes

0x0000000000000000

Performance

- Page table resides in real memory (DRAM)
- A 32-bit virtual-to-real translation requires two accesses to page tables, plus the access to the ultimate real address
  - three real accesses for each virtual access
  - 3X slowdown!
- A 64-bit virtual-to-real translation requires four accesses to page tables, plus the access to the ultimate real address
  - 5X slowdown!

Translation Lookaside Buffers



Quiz 3

Recall that there is a 5x slowdown on memory references via virtual memory on the x86-64. If all references are translated via the TLB, the slowdown will be

a) 1x
b) 2x
c) 3x
d) 4x

OS Role in Virtual Memory

- Memory is like a cache
  - quick access if what's wanted is mapped via page table
  - slow if not — OS assistance required
- OS
  - make sure what's needed is mapped in
  - make sure what's no longer needed is not mapped in

Mechanism

- Program references memory
  - if reference is mapped, access is quick
    - » even quicker if translation in TLB and referent in on-chip cache
  - if not, page-translation fault occurs and OS is invoked
    - » determines desired page
    - » maps it in, if legal reference

Issues

- Fetch policy
  - when are items put in the cache?
- Placement policy
  - where do they go in the cache?
- Replacement policy
  - what's removed to make room?

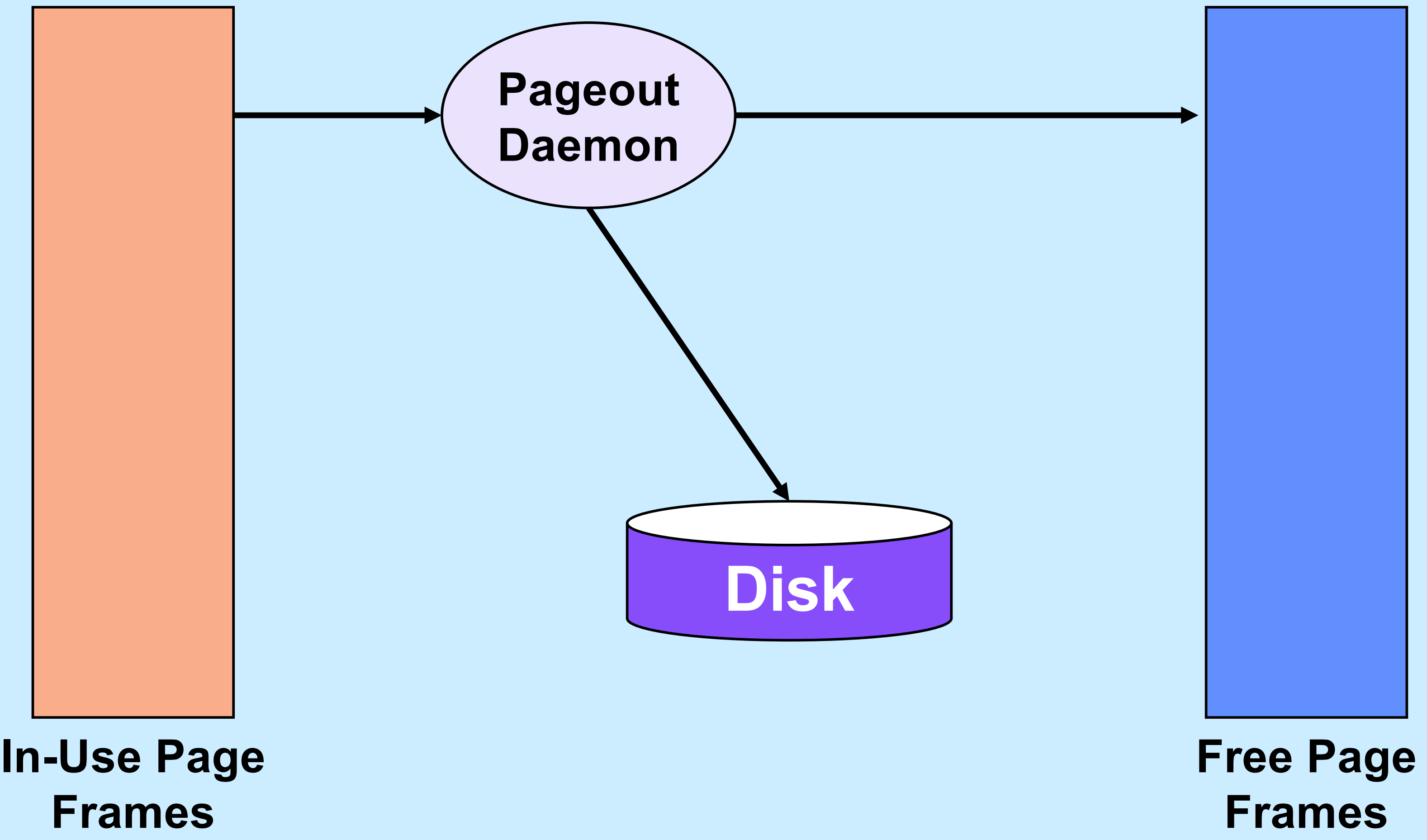
Hardware Caches

- Fetch policy
  - when are items put in the cache?
    - » when they're referenced
    - » prefetch might be possible (e.g., for sequential access)
- Placement policy
  - where do they go in the cache?
    - » usually determined by cache architecture
    - » if there's a choice, it's typically a random choice
- Replacement policy
  - what's removed to make room?
    - » usually determined by cache architecture
    - » if there's a choice, it's typically a random choice

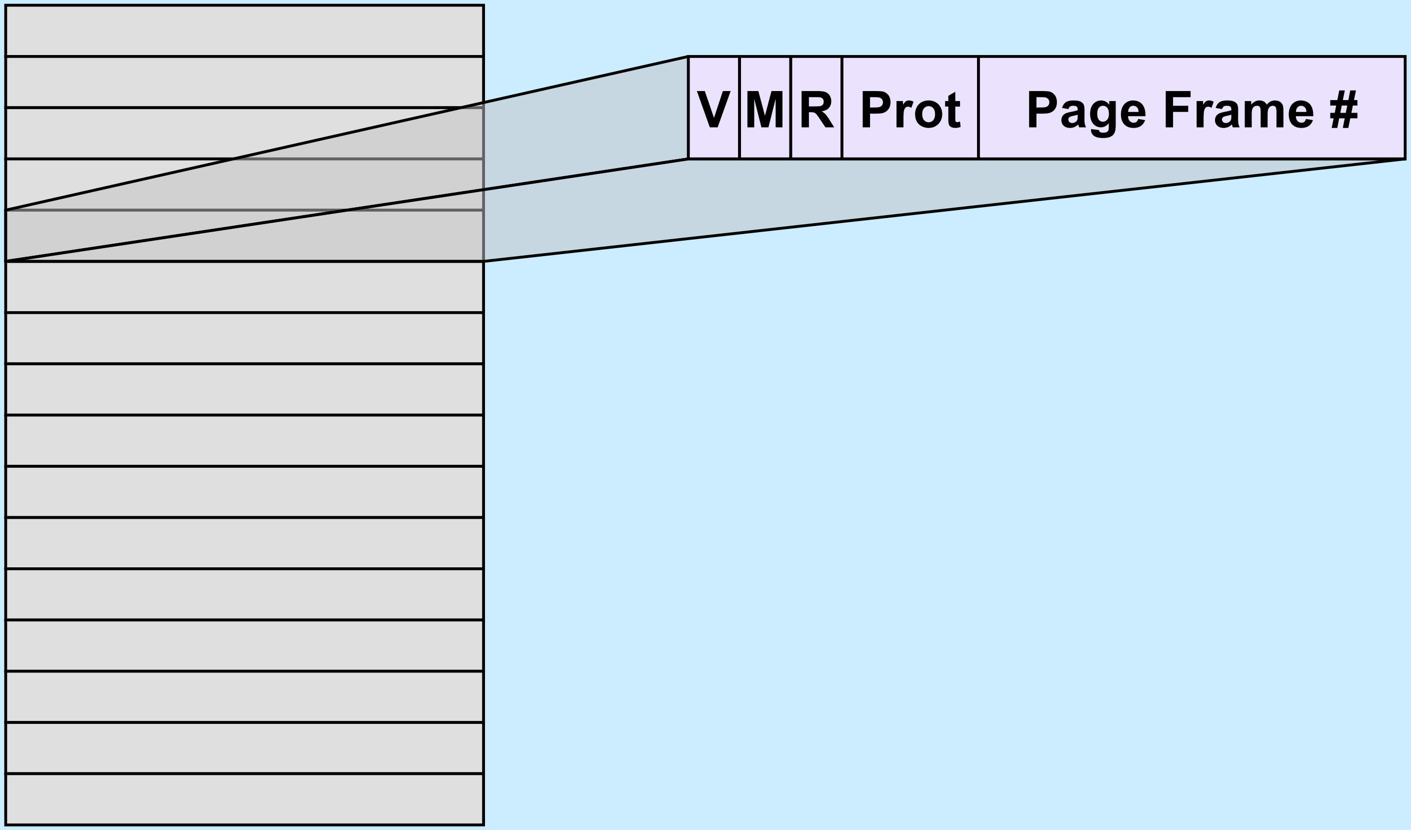
Software Caches

- Fetch policy
  - when are items put in the cache?
    - » when they're referenced
    - » prefetch might be easier than for hardware caches
- Placement policy
  - where do they go in the cache?
    - » usually doesn't matter (no memory is more equal than others)
- Replacement policy
  - what's removed to make room?
    - » would like to remove that whose next use is farthest in future
    - » instead, remove that whose last reference was farthest in the past

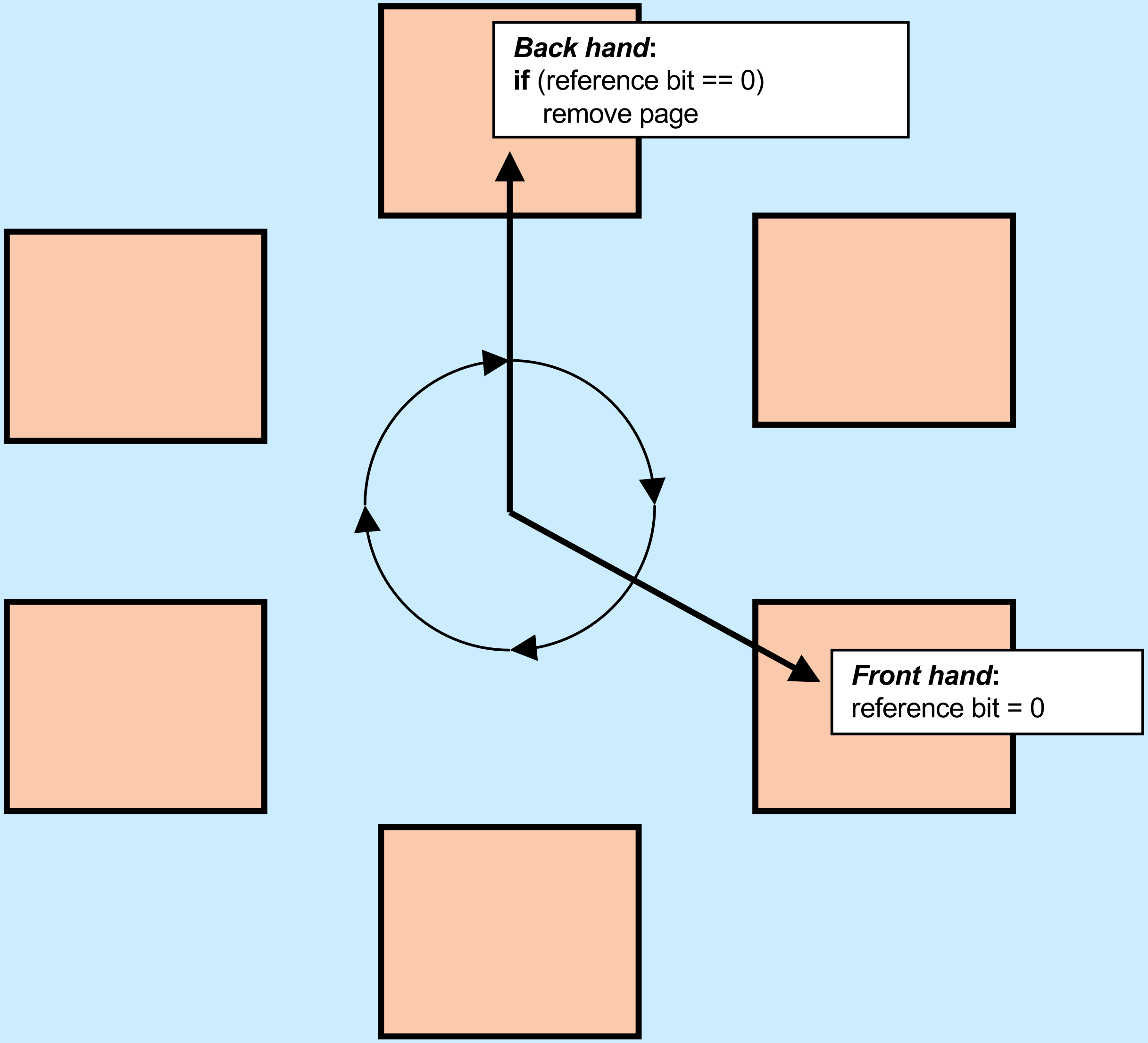
The “Pageout Daemon”



Managing Page Frames



Clock Algorithm

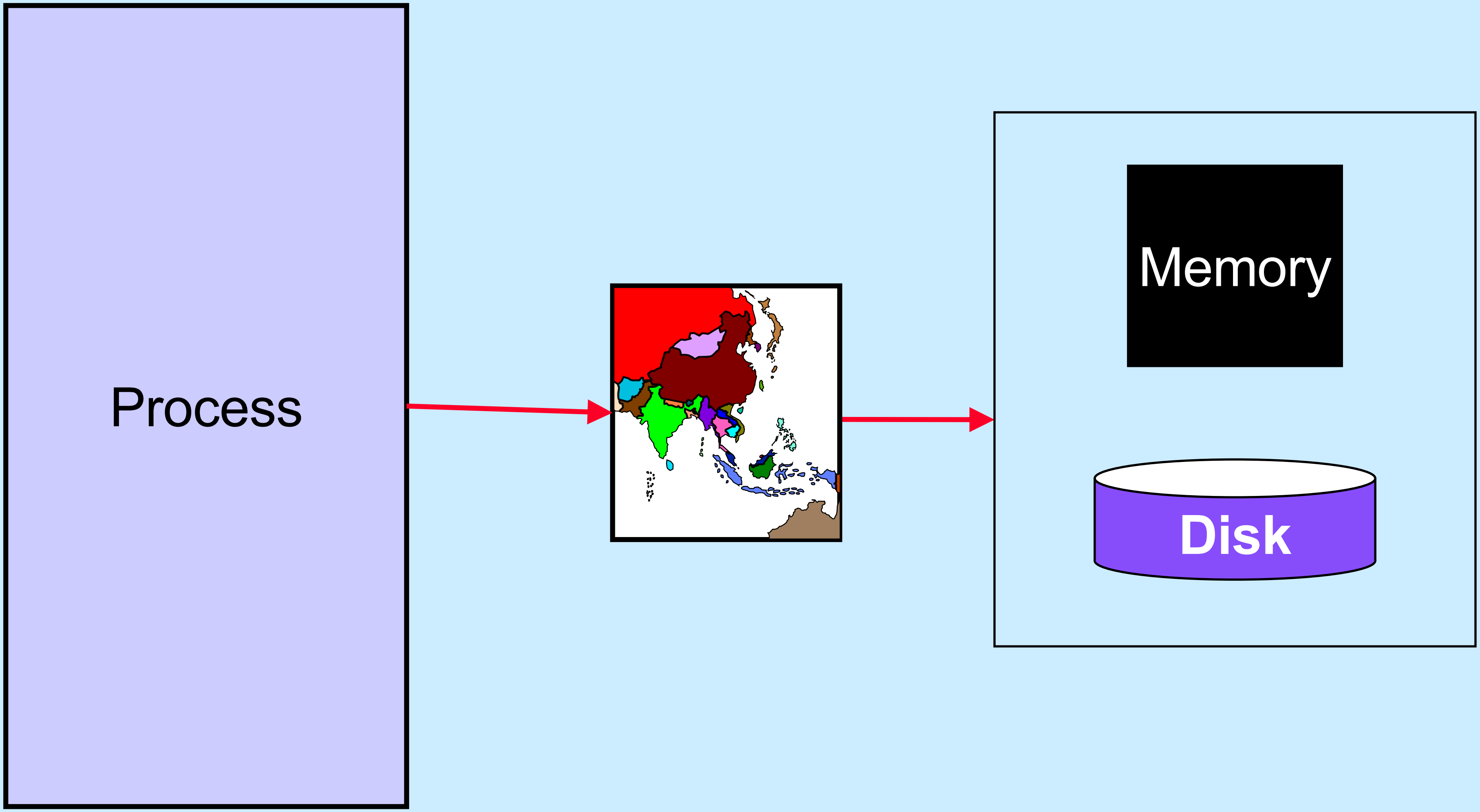


Back hand:
if (reference bit == 0)
    remove page

Front hand:
reference bit = 0

Why is virtual memory used?

More VM than RM

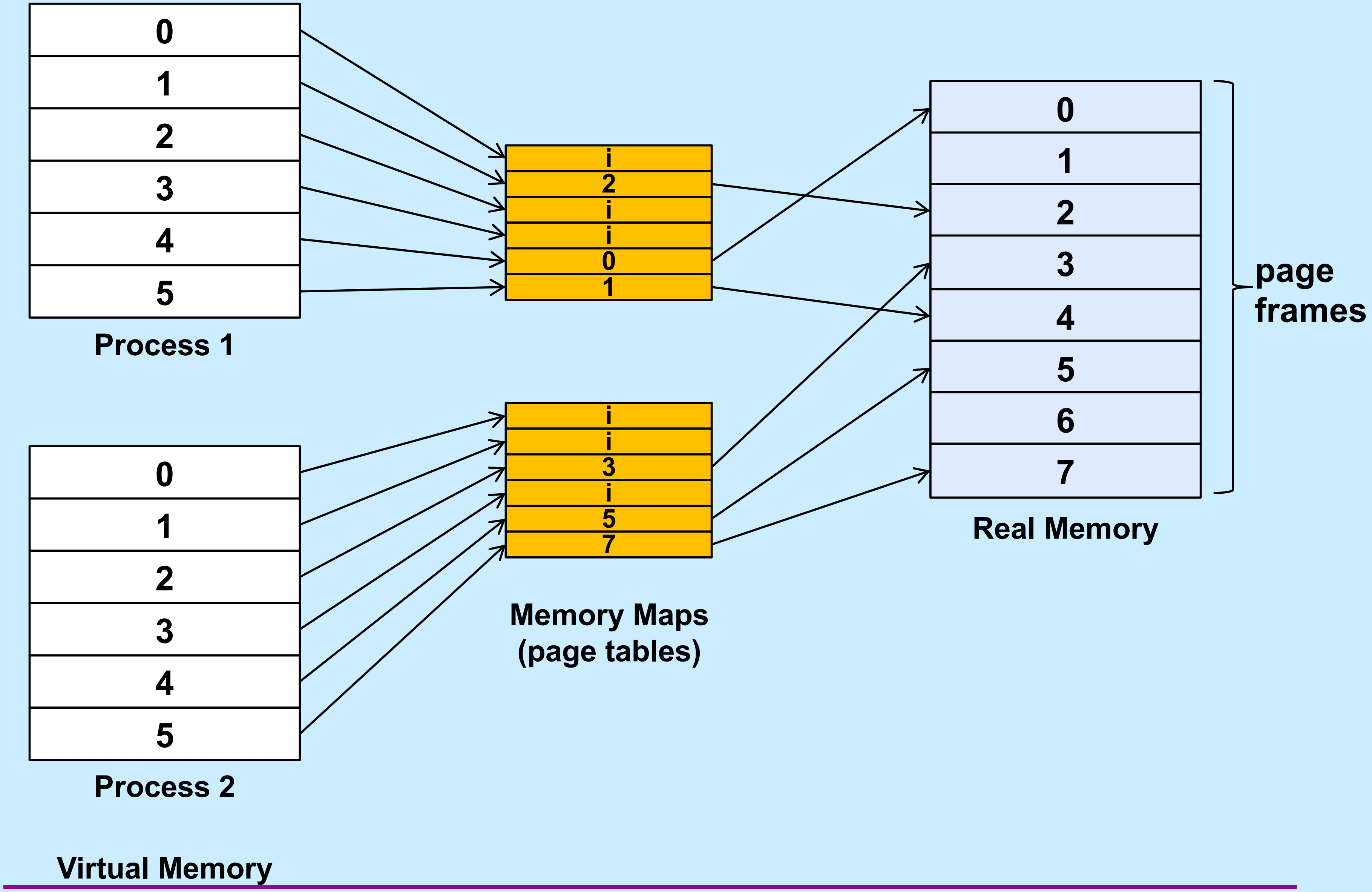


Process

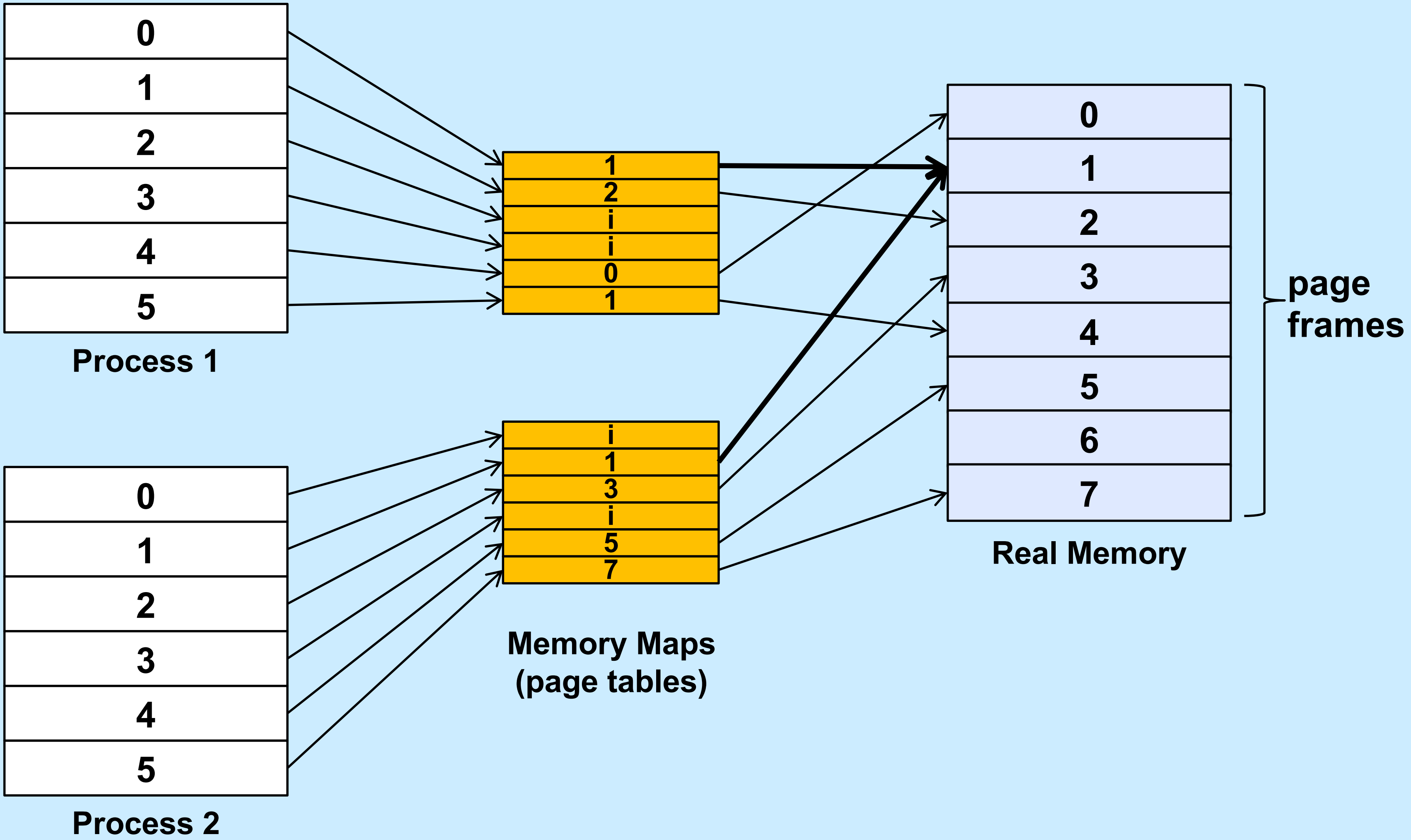
Memory

Disk

Isolation

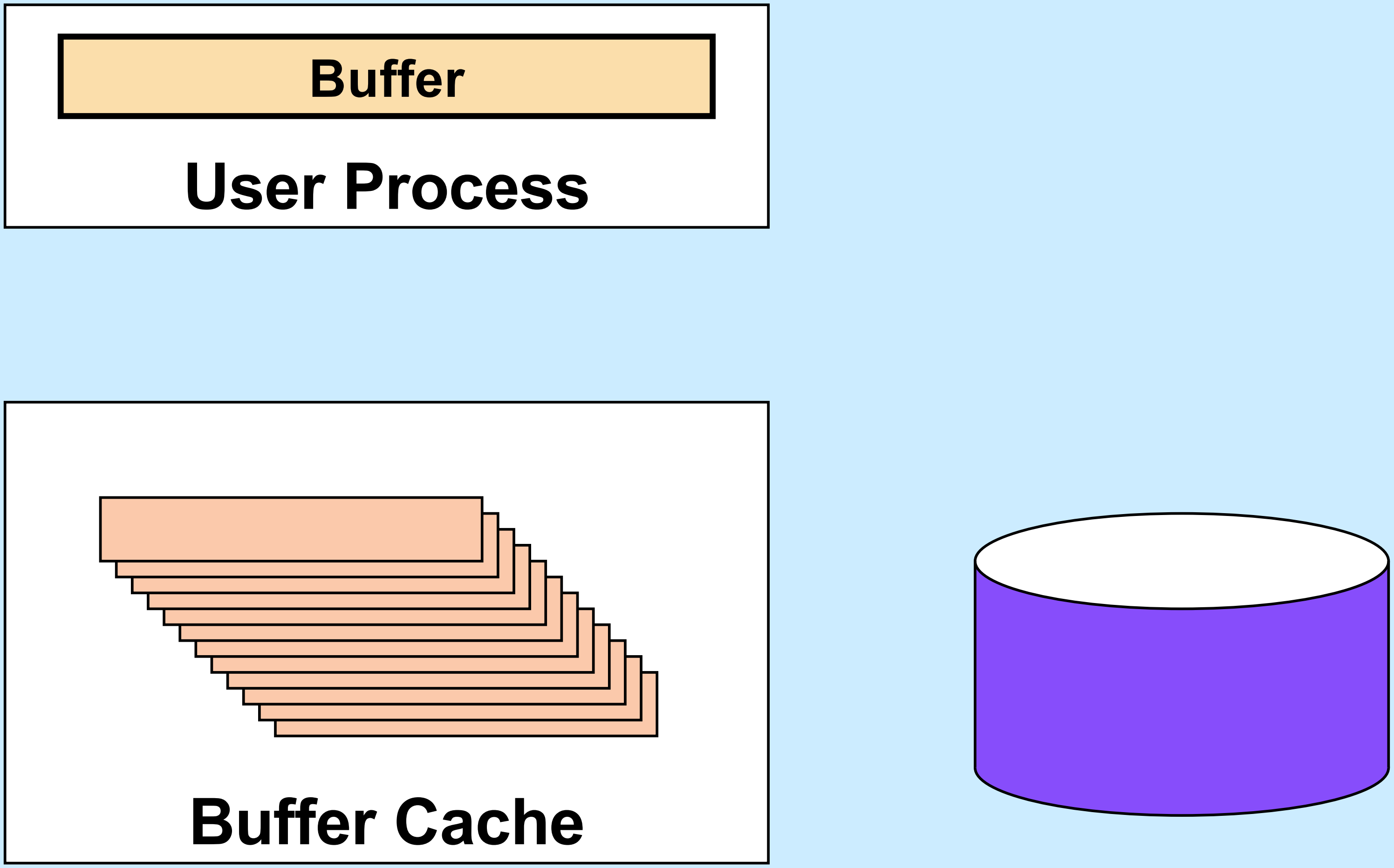

0
1
2
3
4
5
Process 1
i
2
i
i
0
1
0
1
2
3
4
5
6
7
page frames
Real Memory
0
1
2
3
4
5
Process 2
i
i
3
i
5
7
Memory Maps
(page tables)
Virtual Memory

Sharing

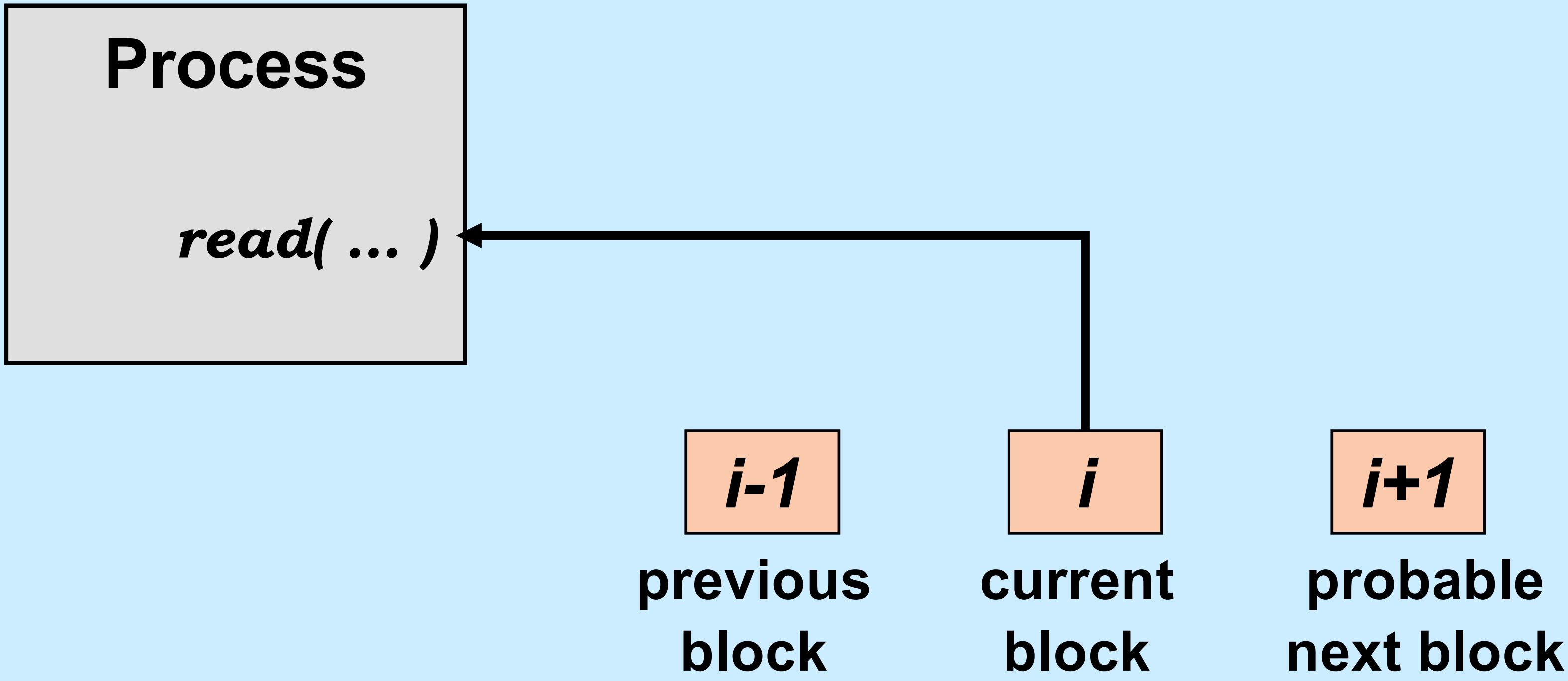


Virtual Memory

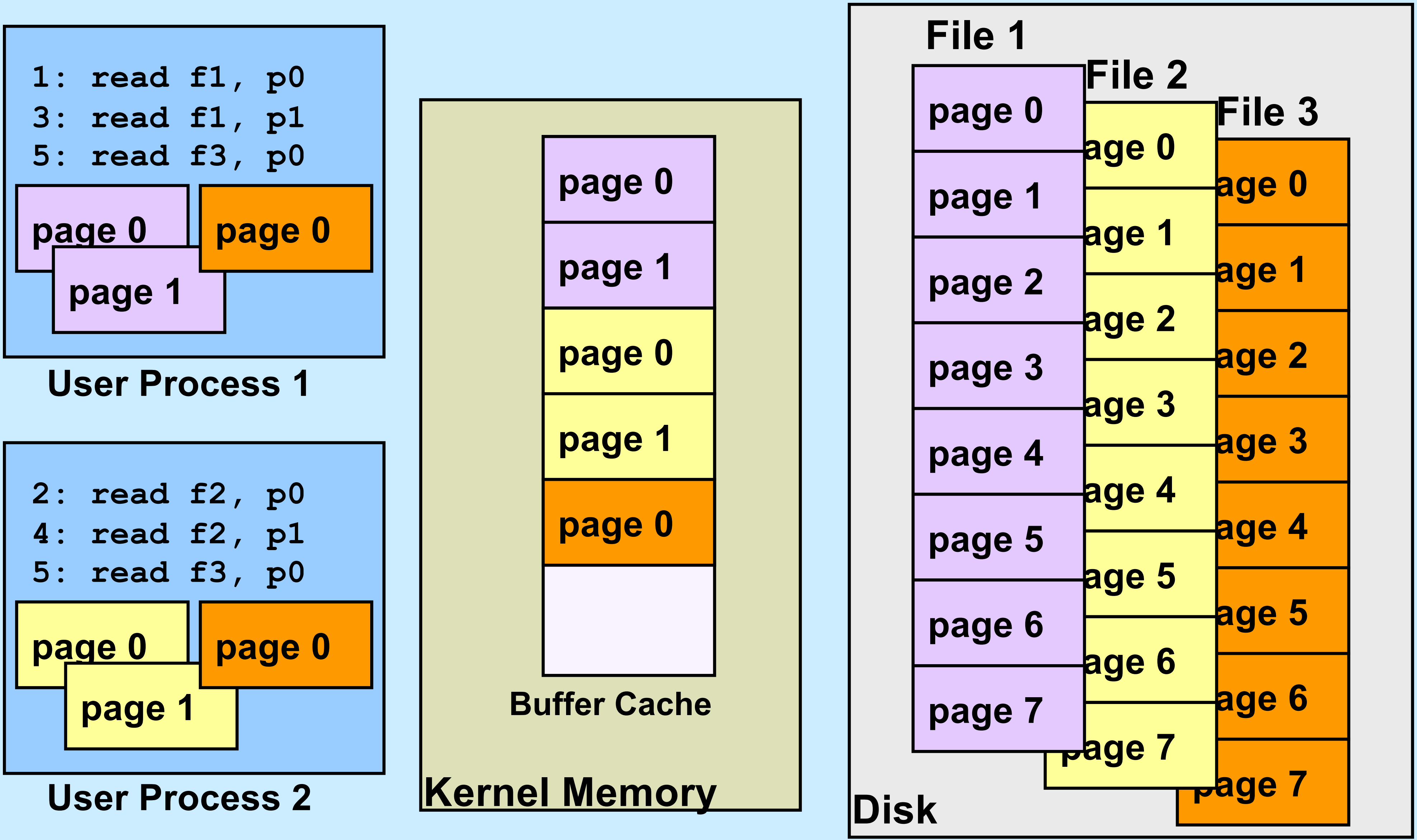
File I/O



Multi-Buffered I/O



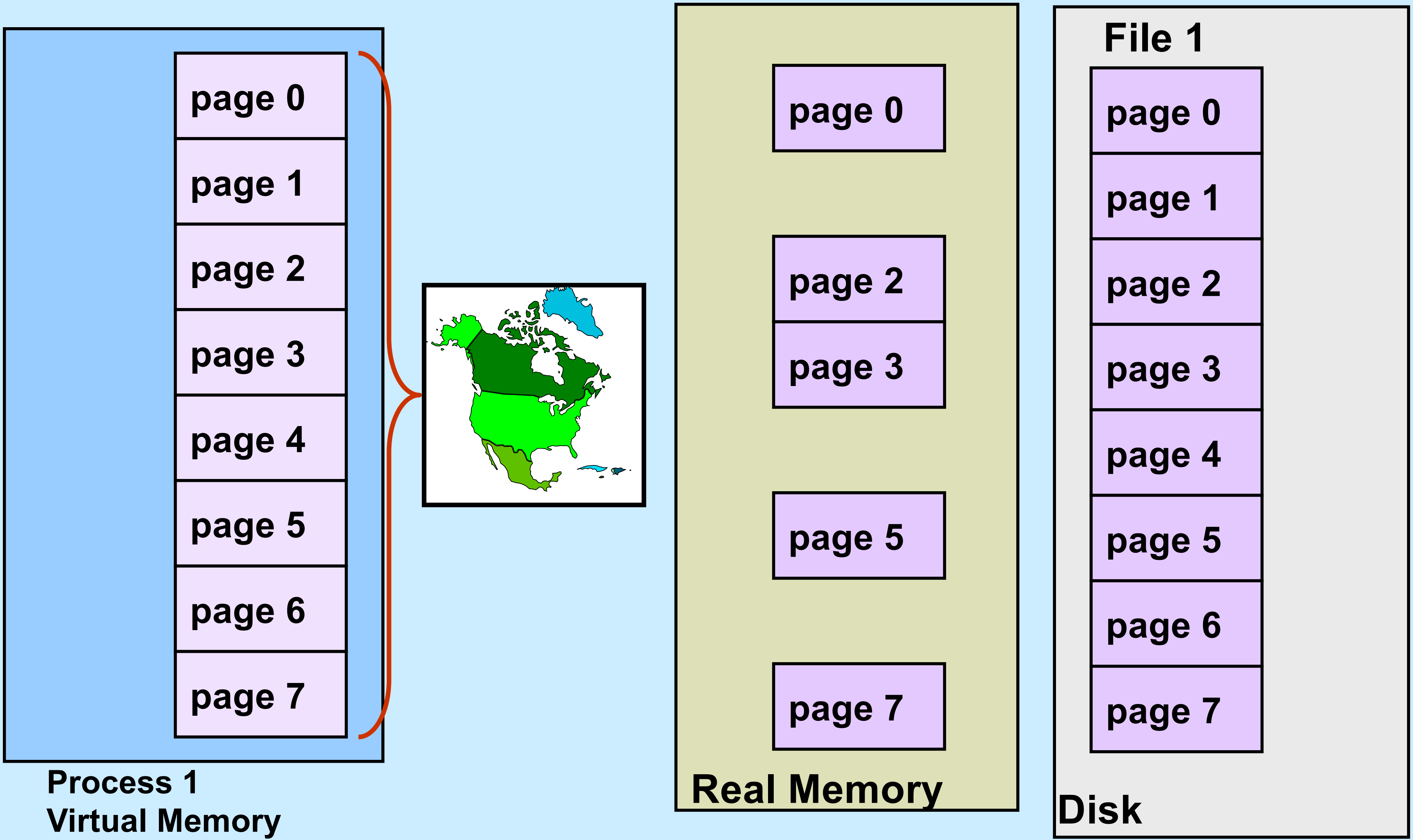
Traditional I/O



```
1: read f1, p0
3: read f1, p1
5: read f3, p0
```

```
2: read f2, p0
4: read f2, p1
5: read f3, p0
```

Mapped File I/O



page 0
page 1
page 2
page 3
page 4
page 5
page 6
page 7

Process 1
Virtual Memory

page 0
page 2
page 3
page 5
page 7

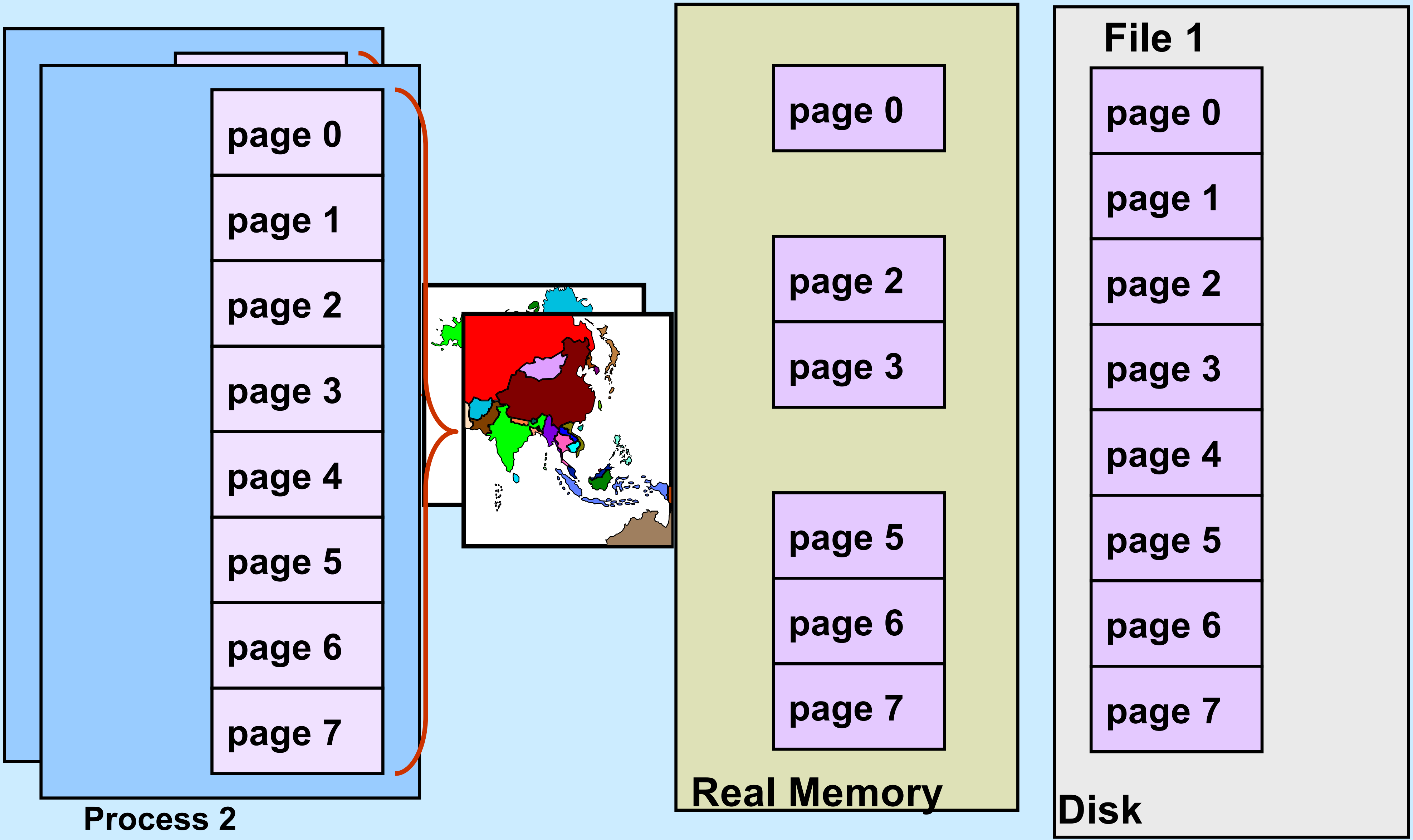
Real Memory

File 1

page 0
page 1
page 2
page 3
page 4
page 5
page 6
page 7

Disk

Multi-Process Mapped File I/O



page 0

page 1

page 2

page 3

page 4

page 5

page 6

page 7

Process 2
Virtual Memory

page 0

page 2

page 3

page 5

page 6

page 7

Real Memory

File 1

page 0

page 1

page 2

page 3

page 4

page 5

page 6

page 7

Disk

Mapped Files

- **Traditional File I/O**

```
char buf[BigEnough];
fd = open(file, O_RDWR);
for (i=0; i<n_recs; i++) {
   read(fd, buf, sizeof(buf));
   use(buf);
}
```

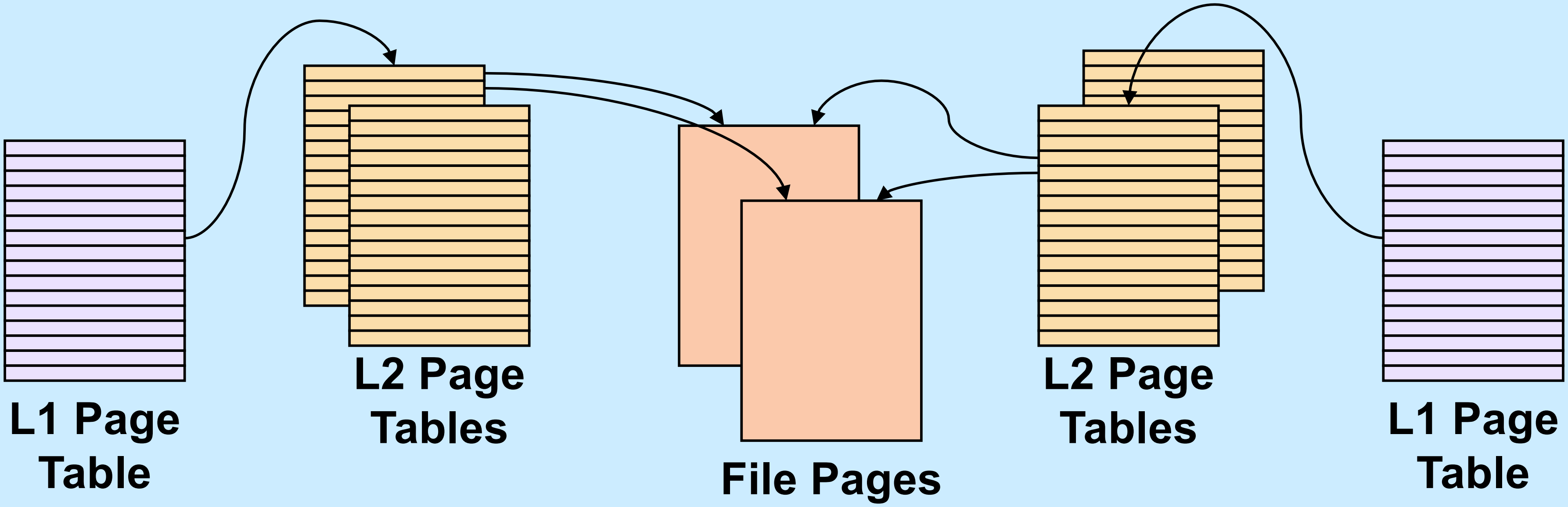
- **Mapped File I/O**

```
record_t *MappedFile;
fd = open(file, O_RDWR);
MappedFile = mmap(... , fd, ...);
for (i=0; i<n_recs; i++)
   use(MappedFile[i]);
```

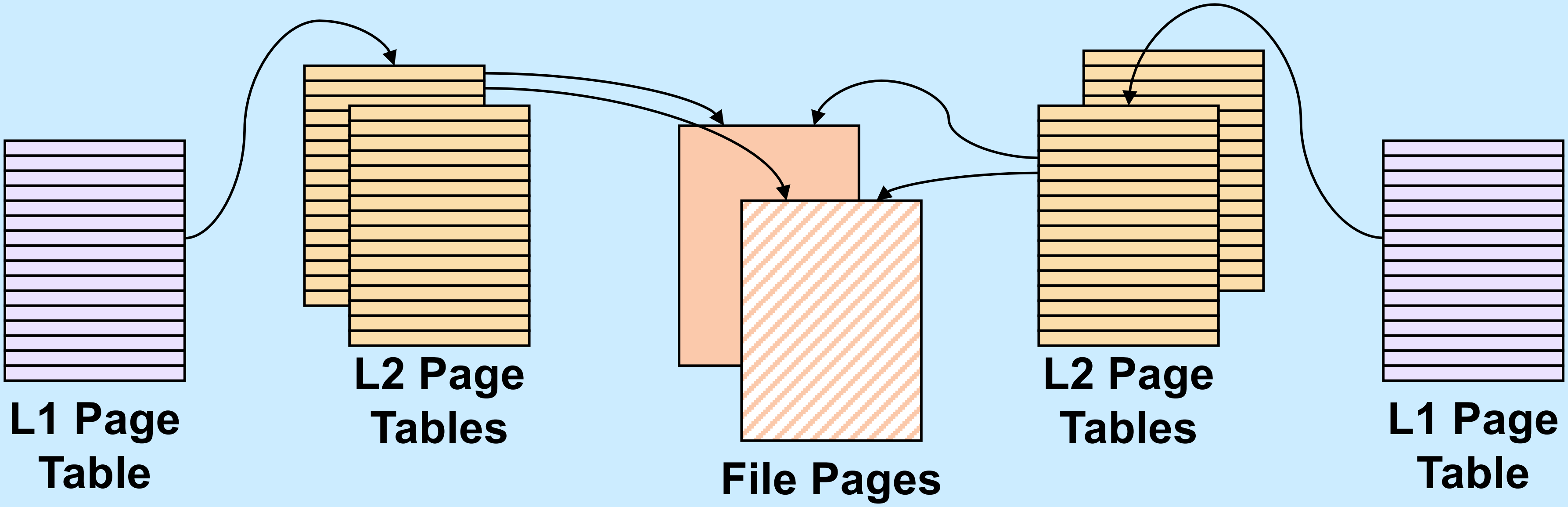
Mmap System Call

```
void *mmap(
  void *addr,
    // where to map file (0 if don’t care)
  size_t len,
    // how much to map
  int prot,
    // memory protection (read, write, exec.)
  int flags,
    // shared vs. private, plus more
  int fd,
    // which file
  off_t off
    // starting from where
  );
```

The *mmap* System Call

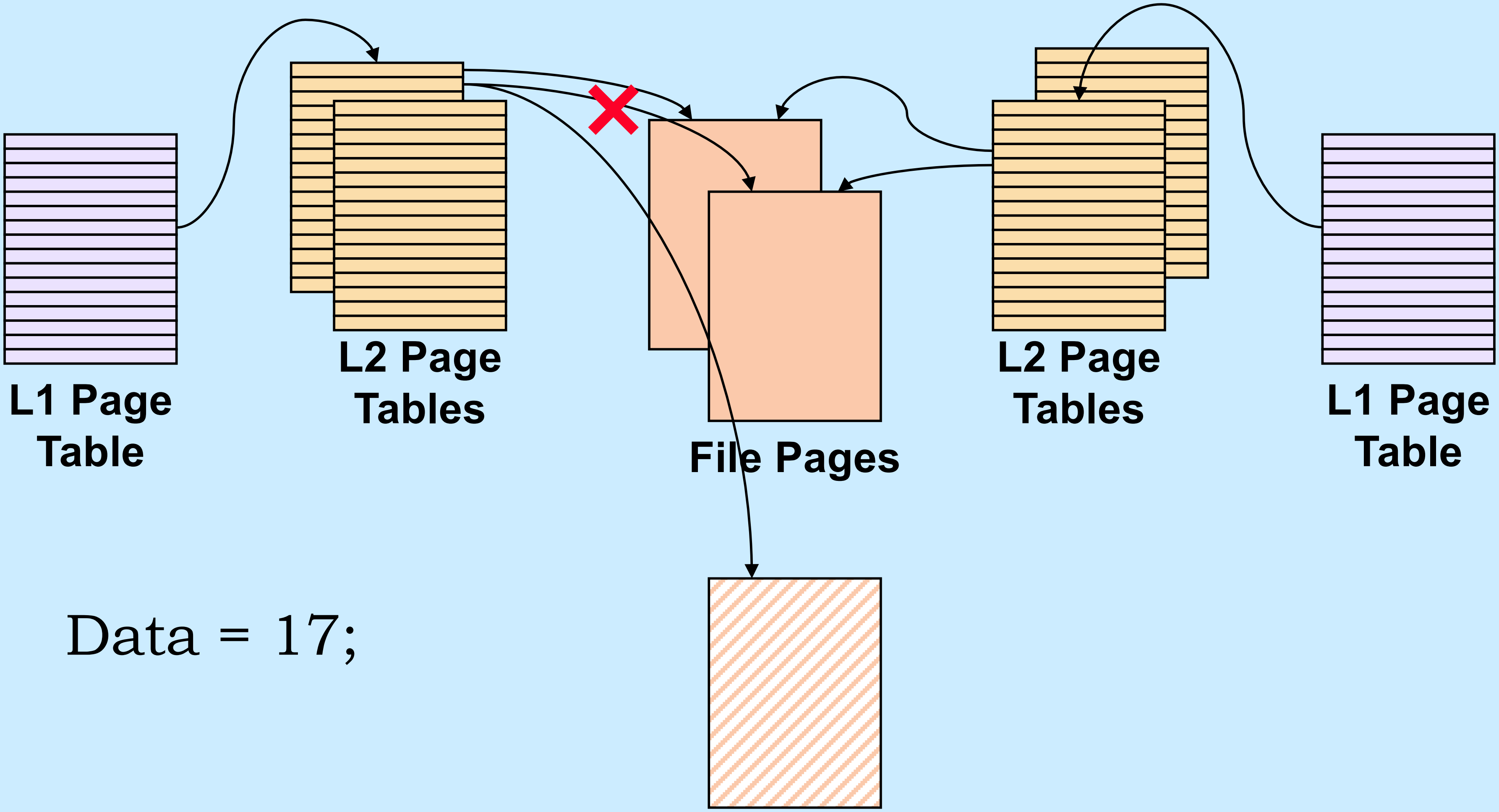


Share-Mapped Files



```
Data = 17;
```

Private-Mapped Files



Data = 17;

Example

```
int main( ) {
  int fd;
  dataObject_t *dataObjectp;

  fd = open("file", O_RDWR);
  if ((int)(dataObjectp = (dataObject_t *)mmap(0,
      sizeof(dataObject_t),
      PROT_READ|PROT_WRITE, MAP_SHARED, fd, 0)) == -1) {
    perror("mmap");
    exit(1);
  }

  // dataObjectp points to region of (virtual) memory
  // containing the contents of the file

  ...

}
```

fork and mmap

```
int main() {
  int x=1;

  if (fork() == 0) {
    // in child
    x = 2;
    exit(0);
  }
  // in parent
  while (x==1) {
    // will loop forever
  }
  return 0;
}
```

```
int main() {
  int fd = open( ... );
  int *xp = (int *)mmap(...,
      MAP_SHARED, fd, ...);
  xp[0] = 1;
  if (fork() == 0) {
    // in child
    xp[0] = 2;
    exit(0);
  }
  // in parent
  while (xp[0]==1) {
    // will terminate
  }
  return 0;
}
```