Principles of Operating Systems

CS 446/646

2. Processes

a. Process Description & Control

b. Threads

c. Concurrency

- ✓ Types of process interaction
- ✓ Race conditions & critical regions
- ✓ Mutual exclusion by busy waiting
- ✓ Mutual exclusion & synchronization
  - mutexes
  - semaphores
  - monitors
  - message passing

d. Deadlocks

2.c Concurrency

Types of process interaction

- Concurrency refers to any form of interaction among processes or threads
  - ✓ concurrency is a fundamental part of O/S design
  - ✓ concurrency includes
    - communication among processes/threads
    - sharing of, and competition for system resources
    - cooperative processing of shared data
    - synchronization of process/thread activities
    - organized CPU scheduling
    - solving deadlock and starvation problems

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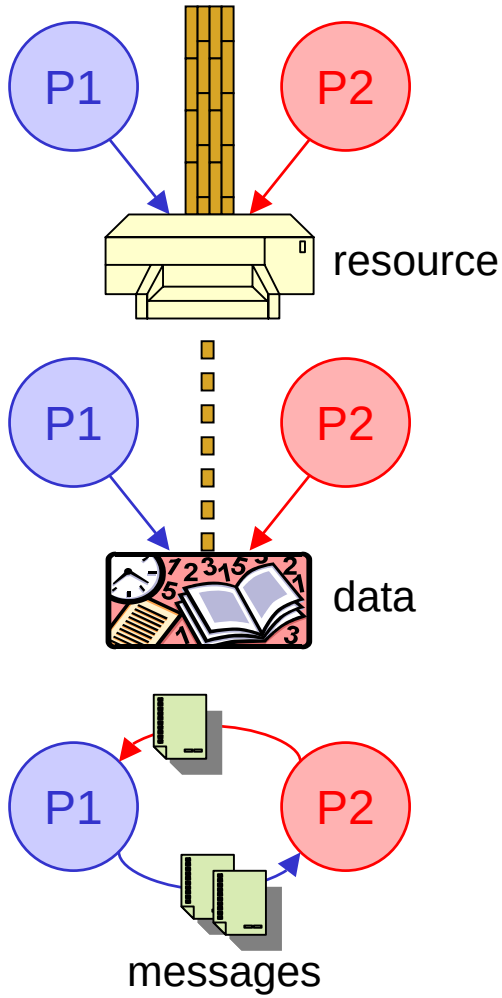
Types of process interaction

- Concurrency arises in the same way at different levels of execution streams
  - ✓ **multiprogramming** — interaction between multiple processes running on one CPU (pseudoparallelism)
  - ✓ **multithreading** — interaction between multiple threads running in one process
  - ✓ **multiprocessors** — interaction between multiple CPUs running multiple processes/threads (real parallelism)
  - ✓ **multicomputers** — interaction between multiple computers running distributed processes/threads
  - → *the principles of concurrency are basically the same in all of these categories (possible differences will be pointed out)*

2.c Concurrency

Types of process interaction

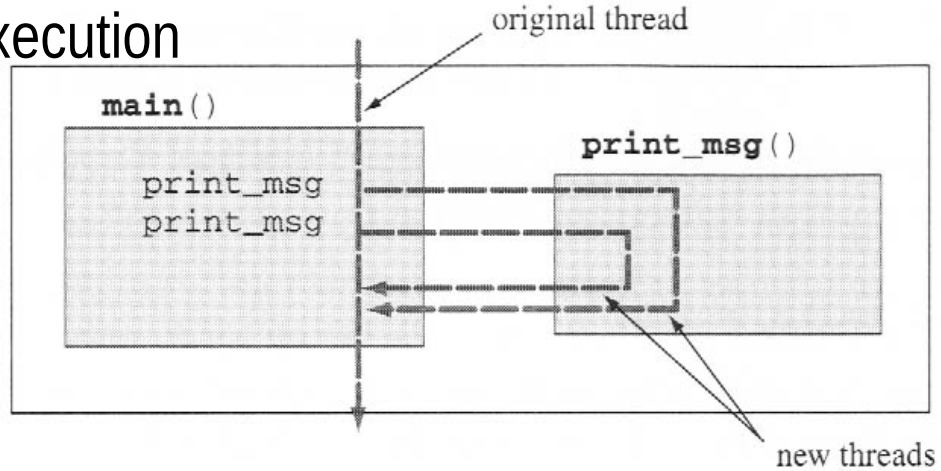
- Whether processes or threads: three basic interactions
  - ✓ processes unaware of each other — they must use shared resources independently, without interfering, and leave them intact for the others
  - ✓ processes indirectly aware of each other — they work on common data and build some result together via the data ("stigmergy" in biology)
  - ✓ processes directly aware of each other — they cooperate by communicating, e.g., exchanging messages



2.c Concurrency

Race conditions & critical regions

- Inconsequential race condition in the shopping scenario
  - ✓ there is a “race condition” if the outcome depends on the order of the execution



Molay, B. (2002) *Understanding Unix/Linux Programming (1st Edition).*

```
> ./multi_shopping
grabbing the salad...
grabbing the milk...
grabbing the apples...
grabbing the butter...
grabbing the cheese...
>
```

```
> ./multi_shopping
grabbing the milk...
grabbing the butter...
grabbing the salad...
grabbing the cheese...
grabbing the apples...
>
```

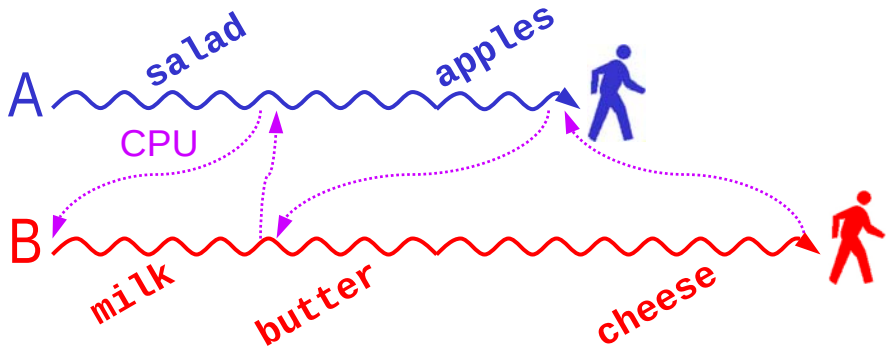
Multithreaded shopping diagram and possible outputs

2.c Concurrency

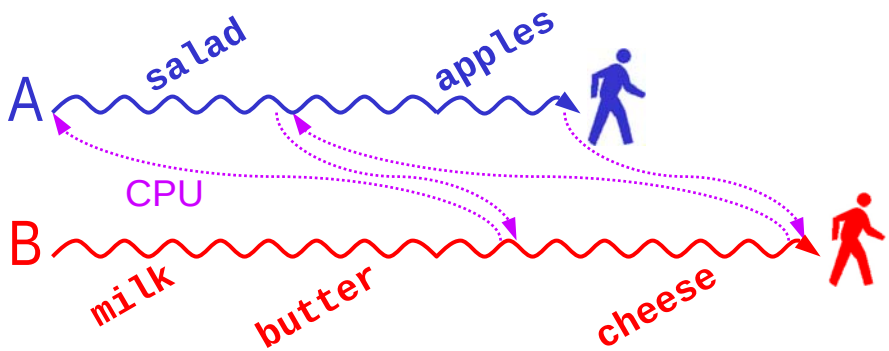
Race conditions & critical regions

- Inconsequential race condition in the shopping scenario
  - ✓ the outcome depends on the CPU scheduling or “interleaving” of the threads (separately, each thread always does the same thing)

```
> ./multi_shopping
grabbing the salad...
grabbing the milk...
grabbing the apples...
grabbing the butter...
grabbing the cheese...
>
```




```
> ./multi_shopping
grabbing the milk...
grabbing the butter...
grabbing the salad...
grabbing the cheese...
grabbing the apples...
>
```

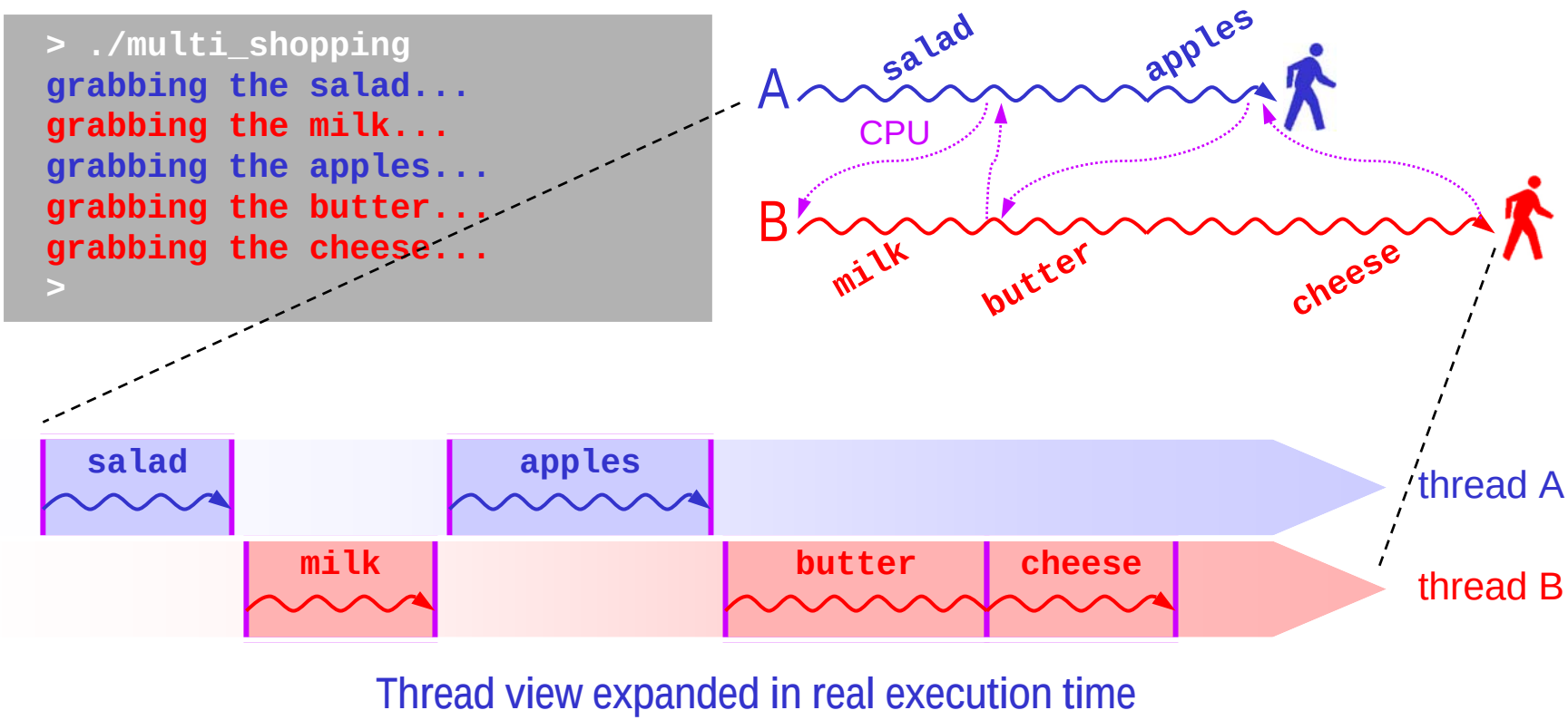


2.c Concurrency

Race conditions & critical regions

- Inconsequential race condition in the shopping scenario
  - ✓ the CPU switches from one process/thread to another, possibly on the basis of a preemptive clock mechanism

```
> ./multi_shopping
grabbing the salad...
grabbing the milk...
grabbing the apples...
grabbing the butter...
grabbing the cheese...
>
```

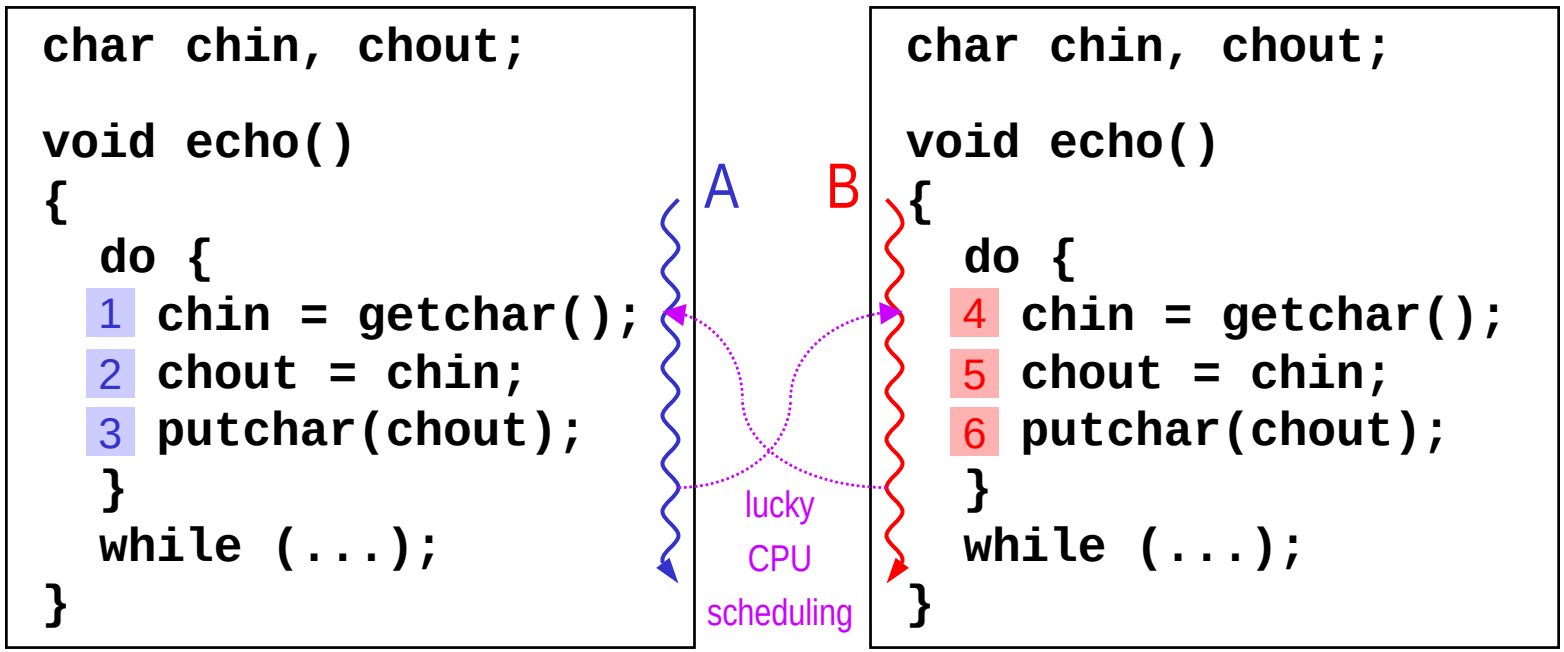


Thread view expanded in real execution time

2.c Concurrency

Race conditions & critical regions

- Consequential race conditions in I/O & variable sharing




```
> ./echo
Hello world!
Hello world!
```

Single-threaded echo

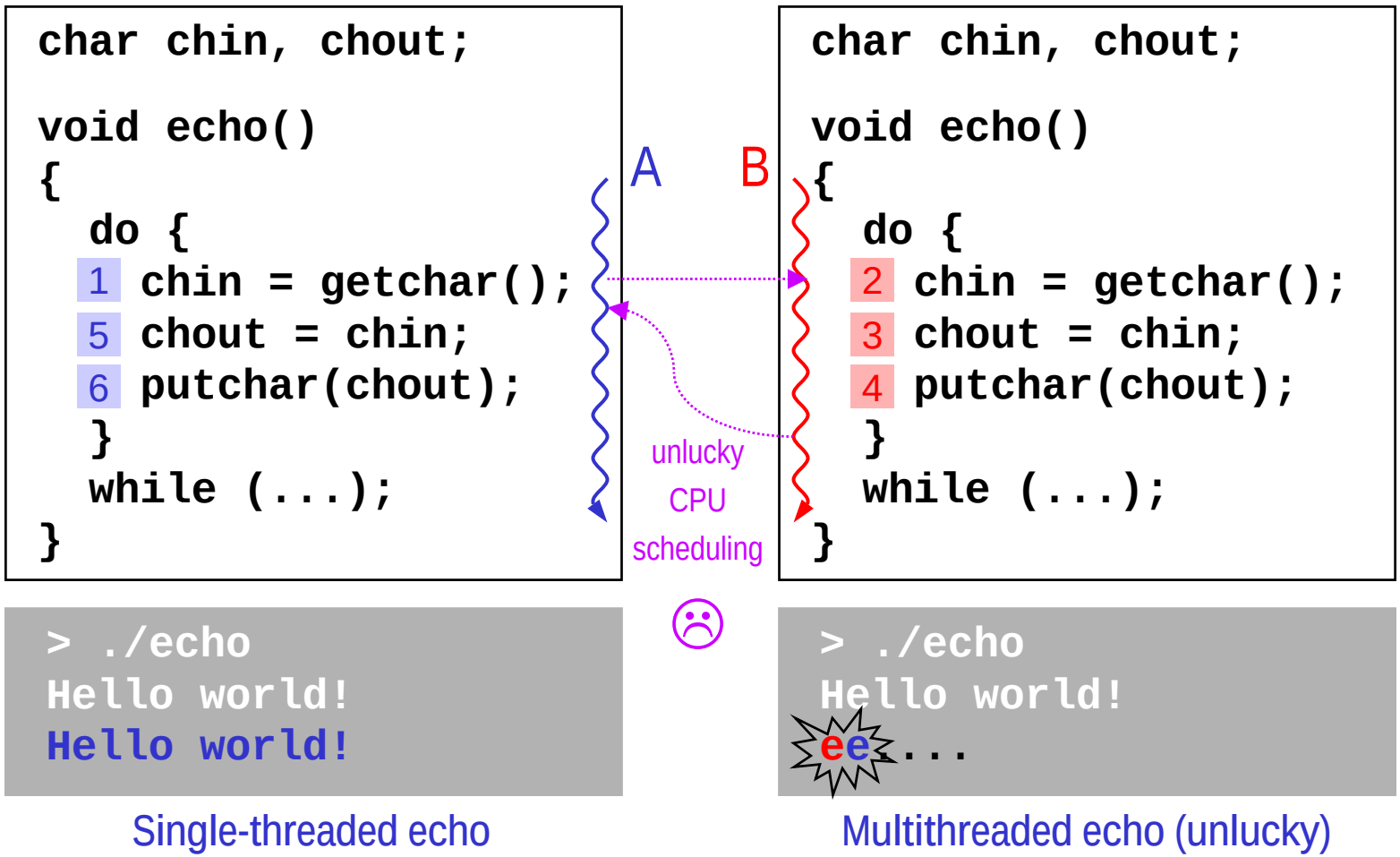
```
> ./echo
Hello world!
Hello world!
```

Multithreaded echo (lucky)

2.c Concurrency

Race conditions & critical regions

- Consequential race conditions in I/O & variable sharing



2.c Concurrency

Race conditions & critical regions

- Consequential race conditions in I/O & variable sharing

changed to local variables →

```
void echo()
{
  char chin, chout;

  do {
1   chin = getchar();
5   chout = chin;
6   putchar(chout);
  }
  while (...);
}
```

A B

unlucky CPU scheduling ☹

```
void echo()
{
  char chin, chout;

  do {
2   chin = getchar();
3   chout = chin;
4   putchar(chout);
  }
  while (...);
}
```

```
> ./echo
Hello world!
Hello world!
```

Single-threaded echo

```
> ./echo
Hello world!
eH...
```

Multithreaded echo (unlucky)

2.c Concurrency

Race conditions & critical regions

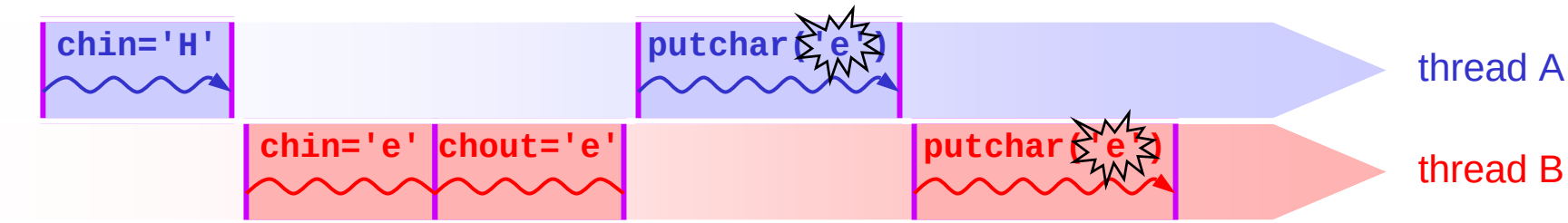
- Consequential race conditions in I/O & variable sharing
  - ✓ note that, in this case, replacing the global variables with local variables did not solve the problem
  - ✓ we actually had two race conditions here:
    - one race condition in the shared variables and the order of value assignment
    - another race condition in the shared output stream: which thread is going to write to output first (this race persisted even after making the variables local to each thread)

→ *generally, problematic race conditions may occur whenever resources and/or data are shared (by processes unaware of each other or processes indirectly aware of each other)*

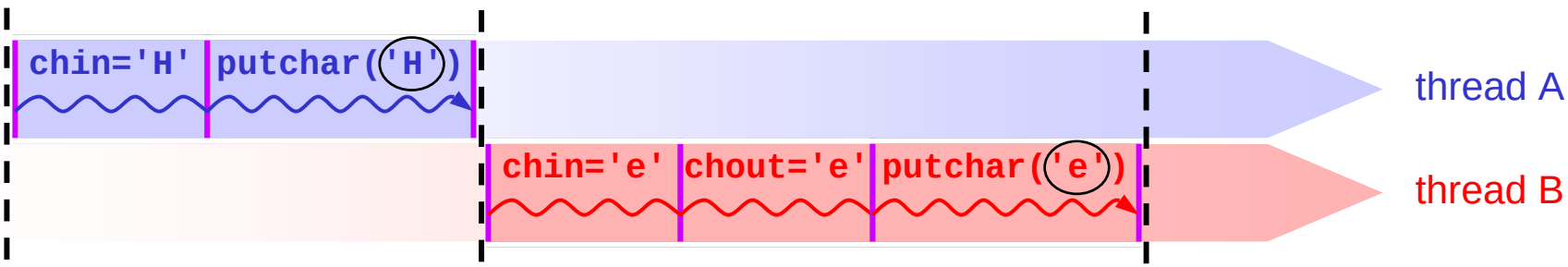
2.c Concurrency

Race conditions & critical regions

- How to avoid race conditions?
  - ✓ find a way to keep the instructions together
  - ✓ this means actually. . . reverting from too much interleaving and going back to “indivisible” blocks of execution!!



(a) too much interleaving may create race conditions



(b) keeping “indivisible” blocks of execution avoids race conditions

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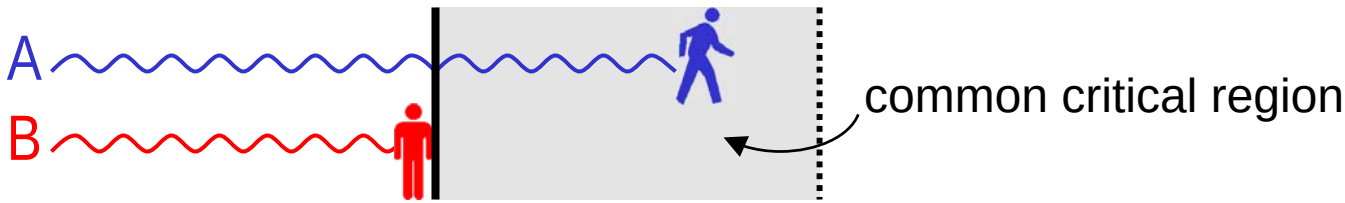
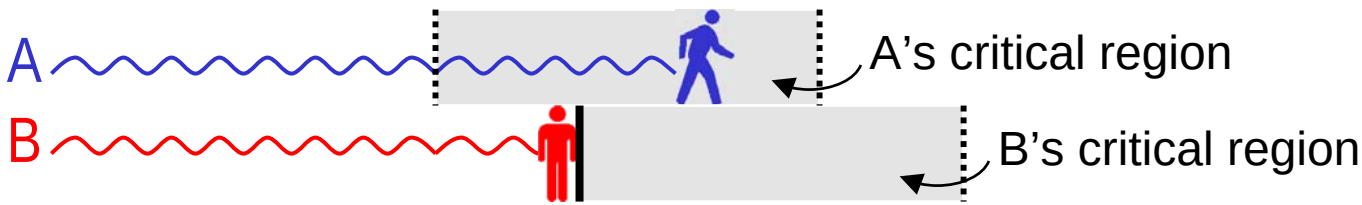
Race conditions & critical regions

- The "indivisible" execution blocks are critical regions
  - ✓ a critical region is a section of code that may be executed by only one process or thread at a time



  - ✓ although it is not necessarily the same region of memory or section of program in both processes

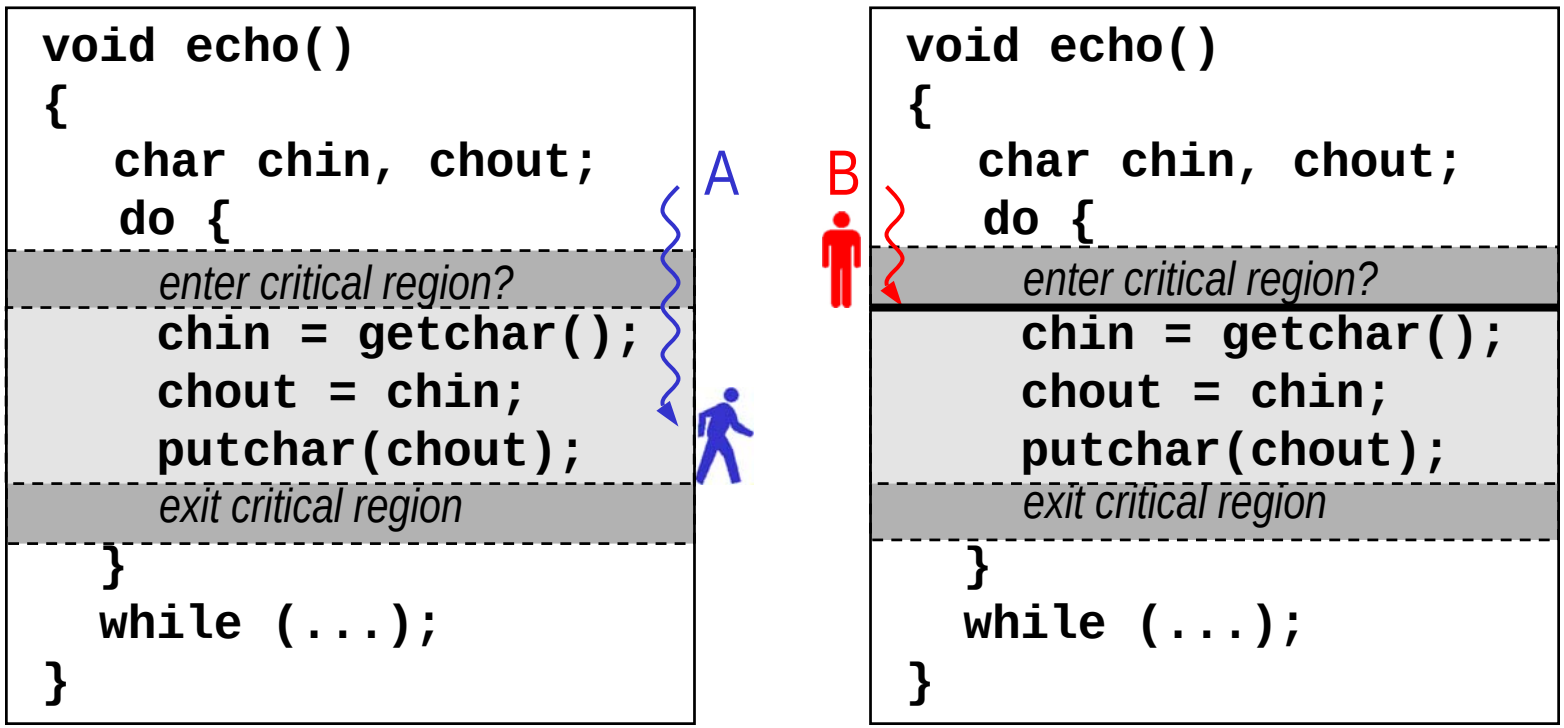


  - → *but physically different or not, what matters is that these regions cannot be interleaved or executed in parallel (pseudo or real)*

2.c Concurrency

Race conditions & critical regions

- We need mutual exclusion from critical regions
  - ✓ critical regions can be protected from concurrent access by padding them with entrance and exit gates (we'll see how later): a thread must try to check in, then it must check out



2.c Concurrency

Race conditions & critical regions

Chart of mutual exclusion

1. **mutual exclusion inside** — only one process at a time may be allowed in a critical region

2. **no exclusion outside** — a process stalled in a *non*critical region may not exclude other processes from their critical regions

3. **no indefinite occupation** — a critical region may be only occupied for a finite amount of time

2.c Concurrency

Race conditions & critical regions

Chart of mutual exclusion (cont'd)

4. **no indefinite delay when barred** — a process may be only excluded for a finite amount of time (no deadlock or starvation)

5. **no delay when about to enter** — a critical region free of access may be entered immediately by a process

6. **nondeterministic scheduling** — no assumption should be made about the relative speeds of processes

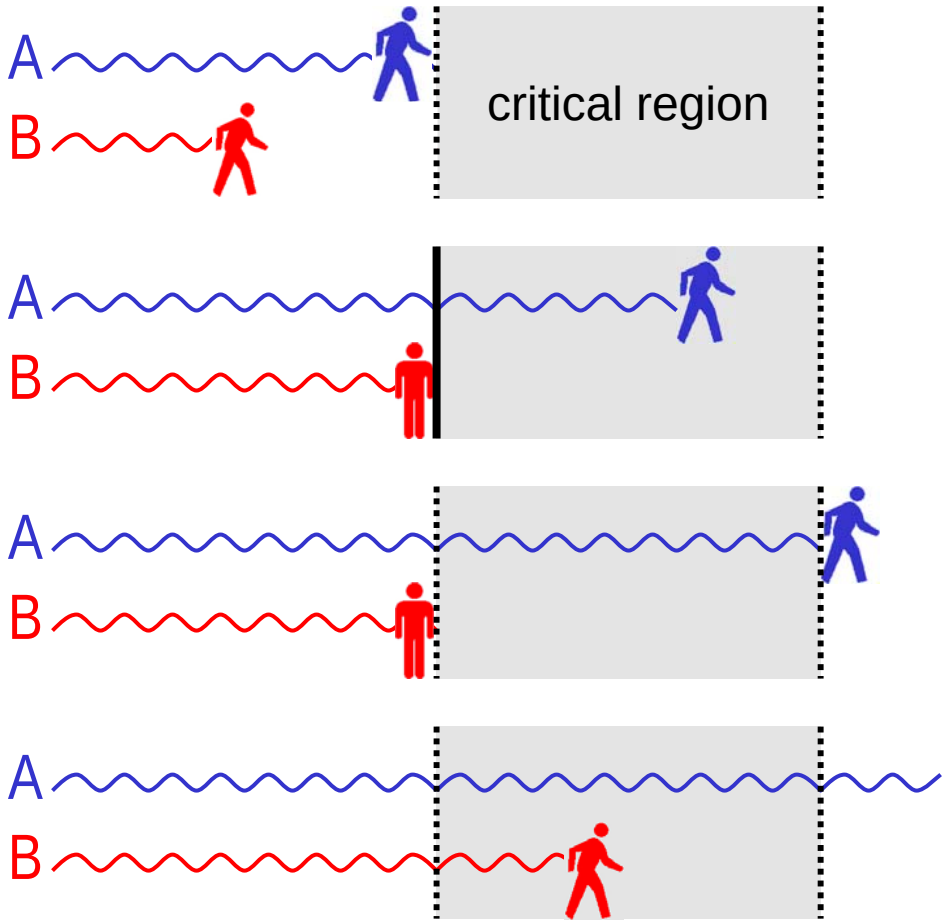
2.c Concurrency

Mutual exclusion by busy waiting

- Desired effect: mutual exclusion from the critical region

HOW is this achieved??

1. thread A reaches the gate to the critical region (CR) before B
2. thread A enters CR first, preventing B from entering (B is waiting or is blocked)
3. thread A exits CR; thread B can now enter
4. thread B enters CR

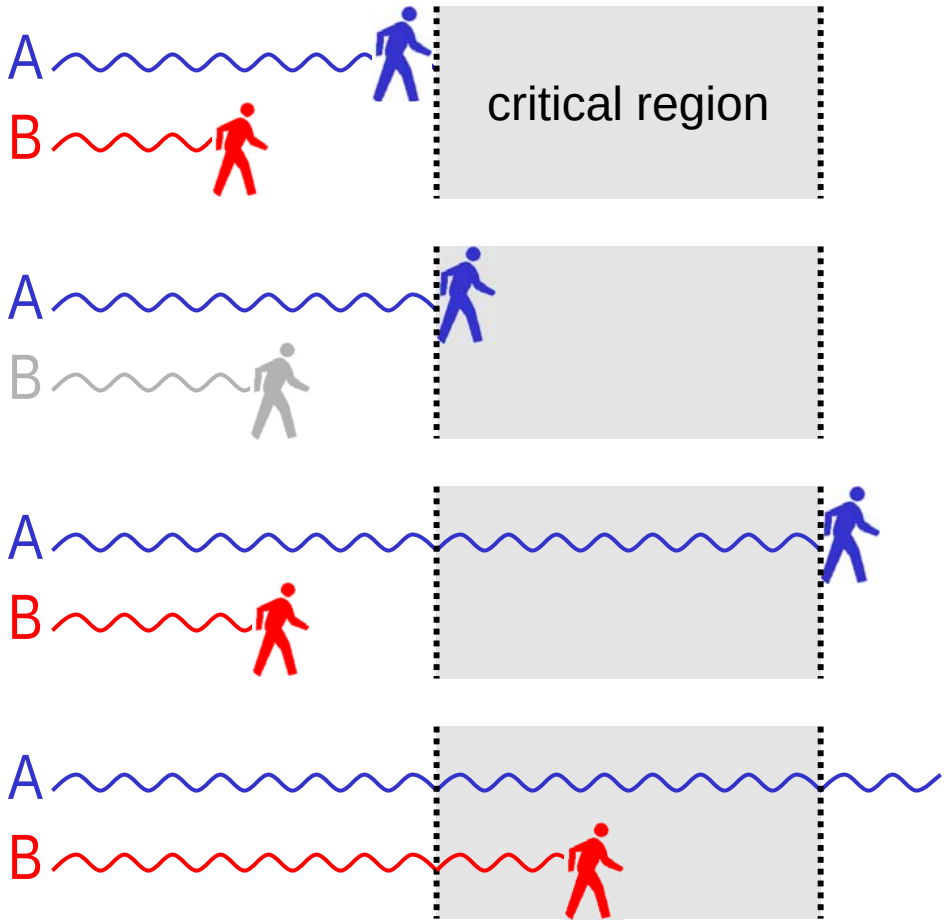


2.c Concurrency

Mutual exclusion by busy waiting

- Implementation 0 — disabling hardware interrupts

1. thread A reaches the gate to the critical region (CR) before B
2. as soon as A enters CR, it disables all interrupts, thus B cannot be scheduled
3. as soon as A exits CR, it reenables interrupts; B can be scheduled again
4. thread B enters CR



2.c Concurrency

Mutual exclusion by busy waiting

- Implementation 0 — ~~disabling hardware interrupts~~ 👎
  - ✓ it works, but is foolish
  - ✓ what guarantees that the user process is going to ever exit the critical region?
  - ✓ meawhile, the CPU cannot interleave any other task, even unrelated to this race condition
  - ✓ the critical region becomes one *physically* indivisible block, not logically
  - ✓ also, this is not working in multi-processors

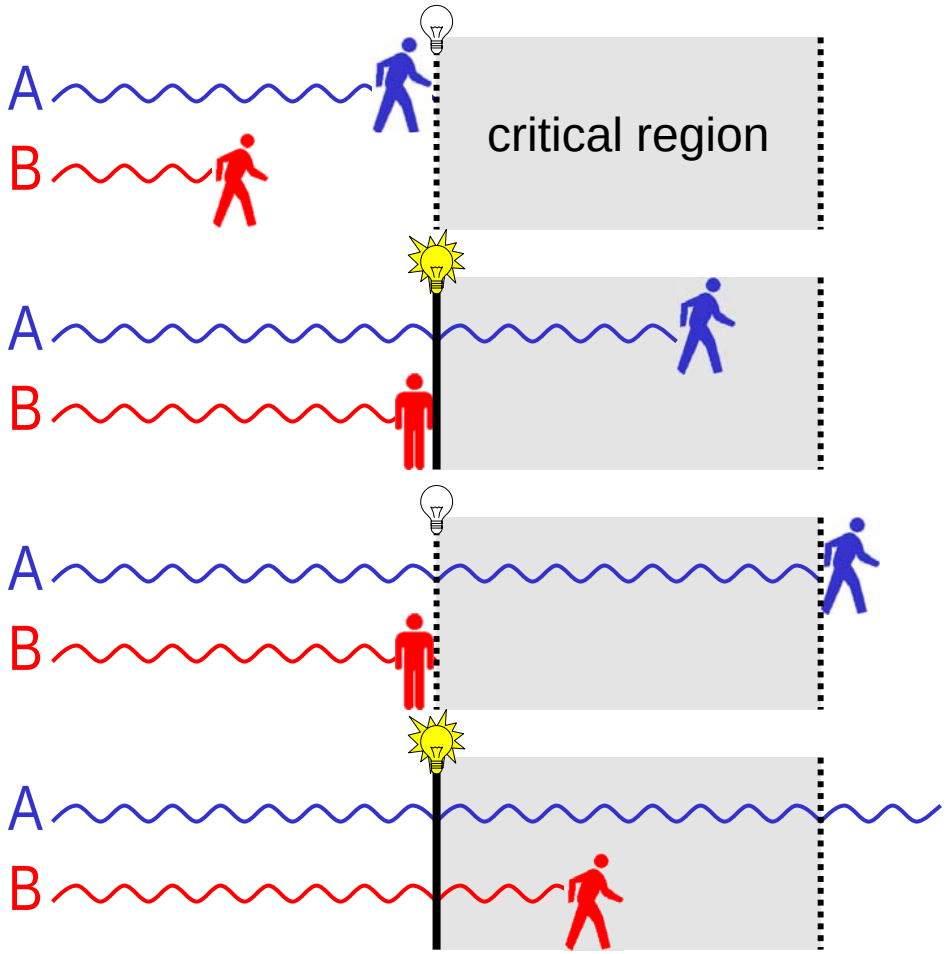
```
void echo()
{
   char chin, chout;
   do {
      disable hardware interrupts
      chin = getchar();
      chout = chin;
      putchar(chout);
      reenable hardware interrupts
   }
   while (...);
}
```

2.c Concurrency

Mutual exclusion by busy waiting

- Implementation 1 — simple lock variable

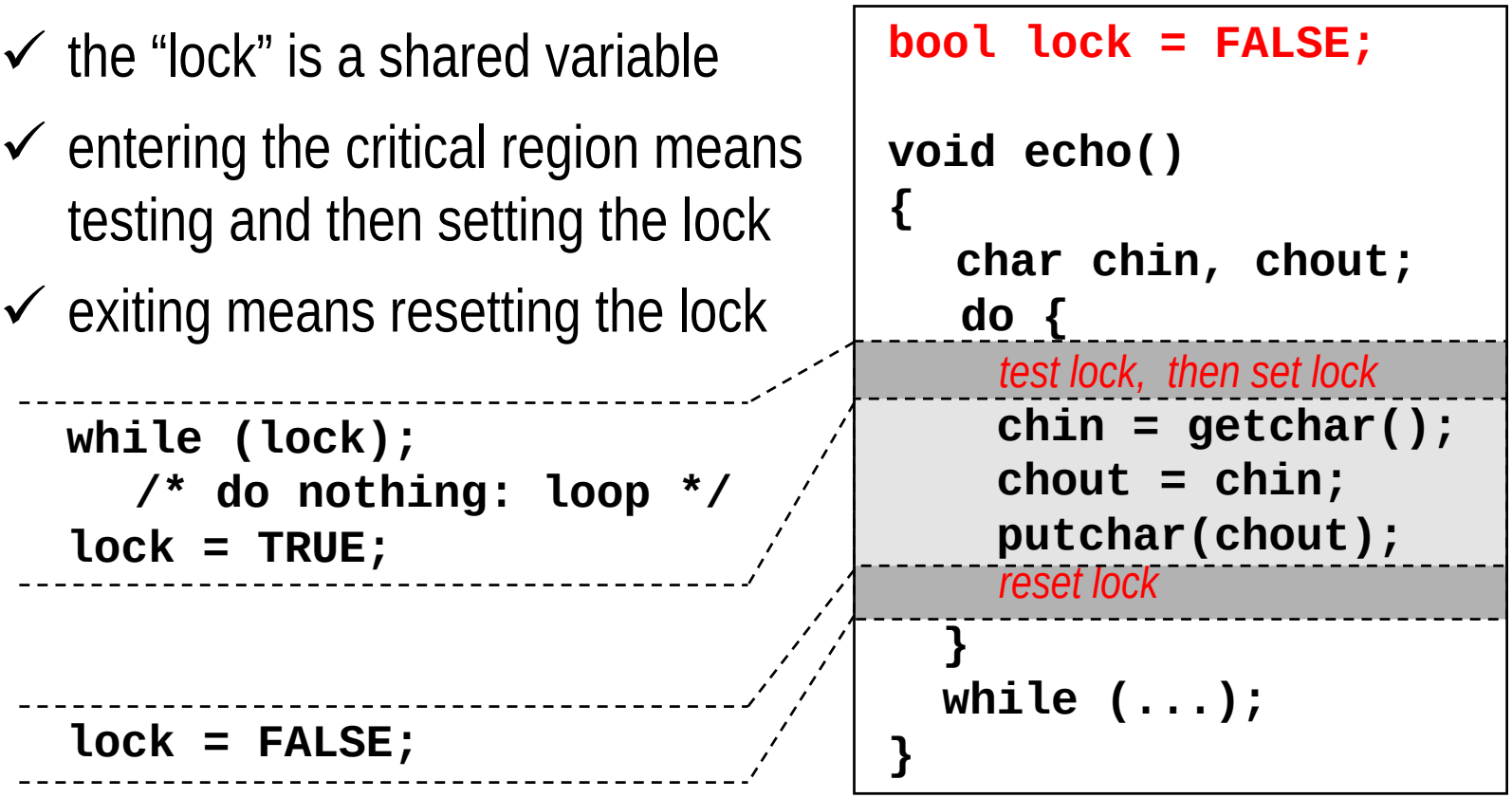
1. thread A reaches CR and finds a lock at 0, which means that A can enter
2. thread A sets the lock to 1 and enters CR, which prevents B from entering
3. thread A exits CR and resets lock to 0; thread B can now enter
4. thread B sets the lock to 1 and enters CR



2.c Concurrency

Mutual exclusion by busy waiting

- Implementation 1 — simple lock variable
  - ✓ the "lock" is a shared variable
  - ✓ entering the critical region means testing and then setting the lock
  - ✓ exiting means resetting the lock



2.c Concurrency

Mutual exclusion by busy waiting

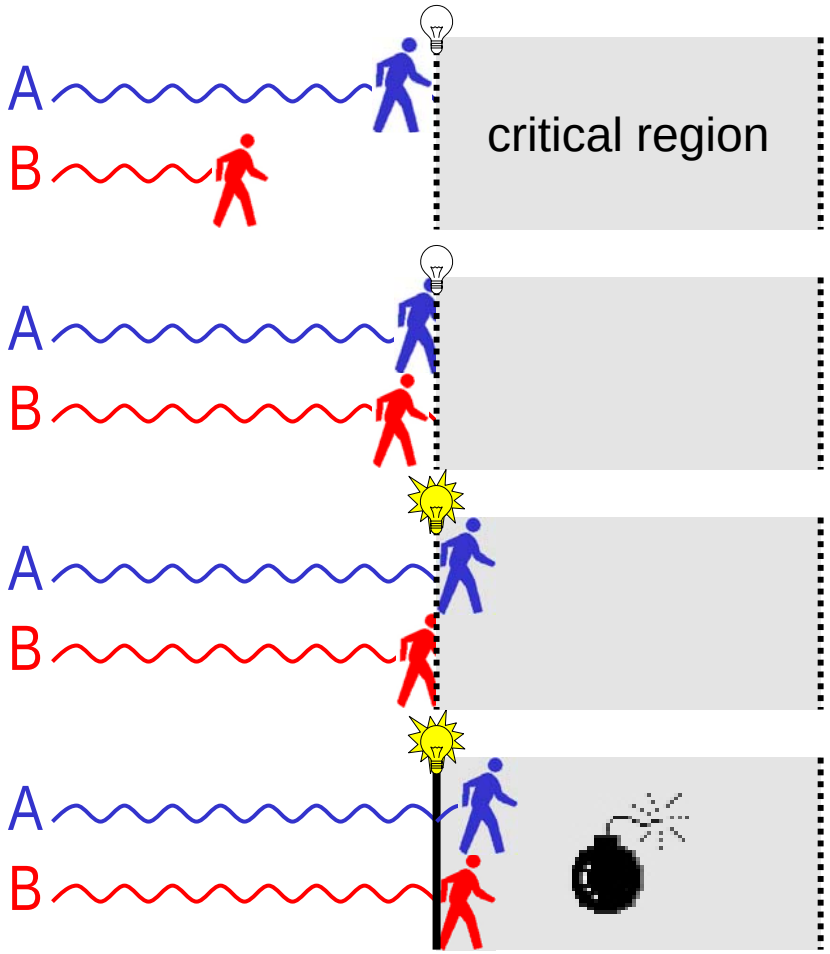
- Implementation 1 — ~~simple lock variable~~ 👎

1. thread A reaches CR and finds a lock at 0, which means that A can enter

1.1 but before A can set the lock to 1, B reaches CR and finds the lock is 0, too

1.2 A sets the lock to 1 and enters CR but cannot prevent the fact that . . .

1.3 . . . B is going to set the lock to 1 and enter CR, too



2.c Concurrency

Mutual exclusion by busy waiting

- Implementation 1 — ~~simple lock variable~~ 👎
  - ✓ suffers from the very flaw we want to avoid: a race condition
  - ✓ the problem comes from the small gap between testing that the lock is off and setting the lock

```
while (lock);   lock = TRUE;
```

  - ✓ it may happen that the other thread gets scheduled exactly inbetween these two actions (falls in the gap)
  - ✓ so they both find the lock off and then they both set it and enter

```
bool lock = FALSE;

void echo()
{
   char chin, chout;
   do {
      test lock, then set lock
      chin = getchar();
      chout = chin;
      putchar(chout);
      reset lock
   }
   while (...);
}
```