	You	**Your Roommate**
3:00	Arrive home	
3:05	Look in fridge, no milk	
3:10	Leave for grocery	
3:15		Arrive home
3:20	Arrive at grocery	Look in fridge, no milk
3:25	Buy milk	Leave for grocery
3:35	Arrive home, put milk in fridge	
3:45		Buy milk
3:50		Arrive home, put up milk
3:50		*Oh no!*

	You	**Your Roommate**
3:00	Arrive home	
3:05	Look in fridge, no milk	
3:06	Look for note; not there	
3:08	Leave ``gone shopping" note	
3:10	Leave for grocery	
3:15		Arrive home
3:20	Arrive at grocery	Look in fridge, no milk
3:26	Buy milk	Read note, relax
3:27	Buy milk	
3:35	Arrive home, put milk in fridge	
3:45		

	Robot you	**Robot Roommate**
3:00.0	Arrive home	
3:00.1		Arrive home
3:00.2	Look in fridge, no milk	
3:00.2	Look for note; not there	Look in fridge, no milk
3:00.3		Look for note; not there
3:00.4	Leave ``gone shopping" note	
3:00.5		Leave ``gone shopping" note
3:00.6	Leave for grocery	
3:02.0		Leave for grocery
3:02.1	Buy milk	Buy milk
3:05.0	Arrive home, put milk in fridge	
3:05.1		Arrive home, spill milk

```
if (no_milk)
  if (no_note) {
    leave_note();
    buy_milk();
    remove_note();
  }
```

```
if (no_milk)
  if (no_note) {
    leave_note();
    buy_milk();
    remove_note();
  }
```

Doesn't work

```
if (no_milk) {
  leave_note();
  if (no_note)
    buy_milk();
  remove_note();
}
```

```
if (no_milk) {
  leave_note();
  if (no_note)
    buy_milk();
  remove_note();
}
```

Doesn't work

```
leave_note(A);
if (no_note(B))
  if (no_milk)
    buy_milk();
remove_note(A);
```

```
leave_note(B);
if (no_note(A))
  if (no_milk)
    buy_milk();
remove_note(B);
```

Doesn't work

Synchronization Pitfalls

- A context switch can occurr *at any time*
  - Even in the middle of a line of code

See **`count_broken.c`**

```
total++     ⇒     mov     total,%eax
                  inc     %eax
                  mov     %eax,total
```

Synchronization Pitfalls

- A context switch can occurr *at any time*
  - Even in the middle of a line of code

- Do not assume anything about process speeds
  - Schedulers are complicated
  - External events change relative speeds

See **`count_broken2.c`**

Synchronization Pitfalls

- A context switch can occurr *at any time*
  - Even in the middle of a line of code

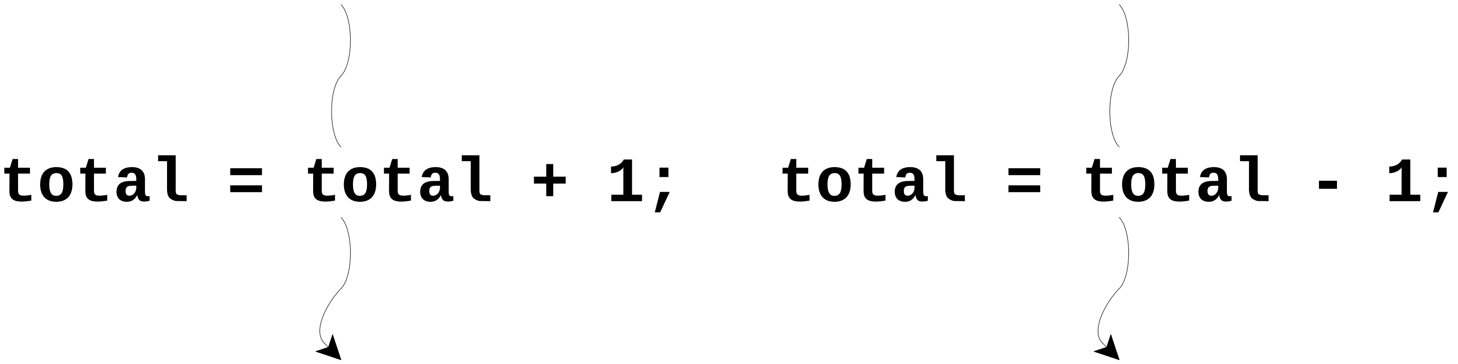
- Do not assume anything about process speeds
  - Schedulers are complicated
  - External events change relative speeds

- A process can exit at any time
  - ... but usually not a thread

- Global memory is an illusion
  - **`volatile`** doesn’t help

Race Condition

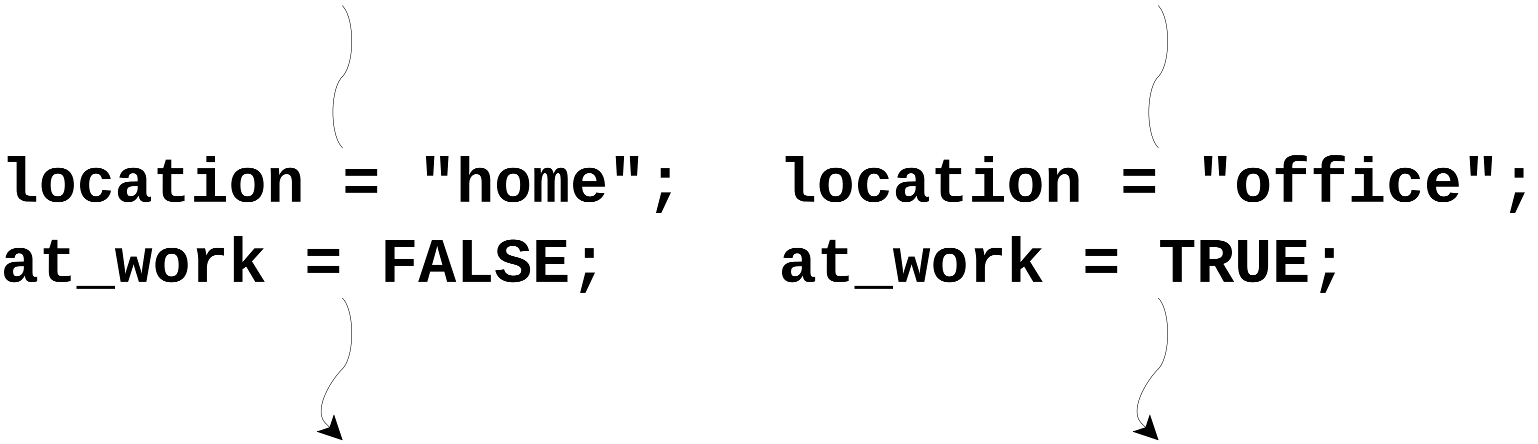
An ***race condition*** is when two threads run concurrently and the order of their actions affects the output in an undesireable way



```
total = total + 1;   total = total - 1;
```

Race Condition

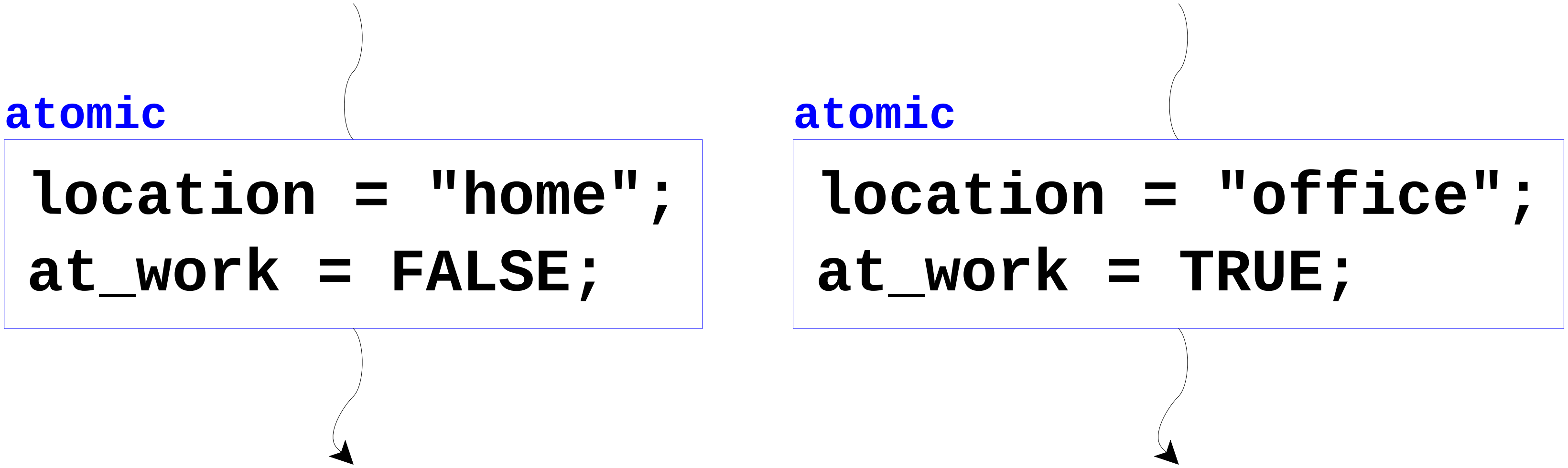
An ***race condition*** is when two threads run concurrently and the order of their actions affects the output in an undesireable way



```
location = "home";   location = "office";
at_work = FALSE;     at_work = TRUE;
```

Atomic Operation

An ***atomic operation*** is a set of instructions to be run apparently instantaneously from the view of ther threads



atomic

```
location = "home";
at_work = FALSE;
```

atomic

```
location = "office";
at_work = TRUE;
```

Critical Section

A ***critical section*** is a region of code that must run atomically

```
void *inc(void *x) {
  int i;

  for (i = 0; i < count; i++)
    total++;

  return NULL;
}
```

Lock

A ***lock*** is a mechanism for making critical sections atomic.

```
void *inc(void *x) {
  int i;

  for (i = 0; i < count; i++) {
    lock();
    total++;
    unlock();
  }

  return NULL;
}
```

Peterson’s Algorithm

```
int flag[2], turn;

void lock(int self /* 0 or 1 */) {
  flag[self] = 1;
  turn = !self;
  while (flag[!self] && turn == !self);
}

void unlock(int self  /* 0 or 1 */) {
  flag[self] = 0;
}


...
lock(self);
```

critical section

```
unlock(self);
...
```

Peterson’s Algorithm

```
void lock(int self /* 0 or 1 */) {
  flag[self] = 1;
  turn = !self;
  while (flag[!self] && turn == !self);
}

flag[self] = 1
turn = !self
if (!flag[!self]) break
if (turn == self) break
if (!flag[!self]) break
if (turn == self) break
...
```

Peterson’s Algorithm

```
flag[self] = 1
turn = !self
if (!flag[!self]) break
if (turn == self) break
if (!flag[!self]) break
if (turn == self) break
...
```

Peterson’s Algorithm

```
flag[0] = 1                flag[1] = 1
turn = 1                   turn = 0
if (!flag[1]) break        if (!flag[0]) break
if (turn == 0) break       if (turn == 1) break
if (!flag[1]) break        if (!flag[0]) break
if (turn == 0) break       if (turn == 1) break
...                        ...
```

Peterson’s Algorithm

```
flag[2] = {0, 0};   turn = 0;
```

```
➤ flag[0] = 1
  turn = 1
  if (!flag[1]) break
  if (turn == 0) break
  if (!flag[1]) break
  if (turn == 0) break
  ...
```

```
➤ flag[1] = 1
  turn = 0
  if (!flag[0]) break
  if (turn == 1) break
  if (!flag[0]) break
  if (turn == 1) break
  ...
```

Peterson’s Algorithm

```
flag[2] = {1, 0};   turn = 0;
```

```
  flag[0] = 1
➤ turn = 1
  if (!flag[1]) break
  if (turn == 0) break
  if (!flag[1]) break
  if (turn == 0) break
  ...
```

```
➤ flag[1] = 1
  turn = 0
  if (!flag[0]) break
  if (turn == 1) break
  if (!flag[0]) break
  if (turn == 1) break
  ...
```

Peterson’s Algorithm

```
        flag[2] = {1, 0};   turn = 1;

  flag[0] = 1               ➤ flag[1] = 1
  turn = 1                    turn = 0
➤ if (!flag[1]) break         if (!flag[0]) break
  if (turn == 0) break        if (turn == 1) break
  if (!flag[1]) break         if (!flag[0]) break
  if (turn == 0) break        if (turn == 1) break
  ...                         ...
```

Peterson’s Algorithm

```
          flag[2] = {1, 0};   turn = 1;

  flag[0] = 1               ➤ flag[1] = 1
  turn = 1                    turn = 0
  if (!flag[1]) break         if (!flag[0]) break
  if (turn == 0) break        if (turn == 1) break
  if (!flag[1]) break         if (!flag[0]) break
  if (turn == 0) break        if (turn == 1) break
  ...                         ...
➤
```

Peterson’s Algorithm

```
      flag[2] = {1, 1};   turn = 1;

  flag[0] = 1                flag[1] = 1
  turn = 1                 ➤ turn = 0
  if (!flag[1]) break        if (!flag[0]) break
  if (turn == 0) break       if (turn == 1) break
  if (!flag[1]) break        if (!flag[0]) break
  if (turn == 0) break       if (turn == 1) break
  ...                        ...
➤
```

Peterson’s Algorithm

```
flag[2] = {1, 1};   turn = 0;

  flag[0] = 1                flag[1] = 1
  turn = 1                   turn = 0
  if (!flag[1]) break      ➤ if (!flag[0]) break
  if (turn == 0) break       if (turn == 1) break
  if (!flag[1]) break        if (!flag[0]) break
  if (turn == 0) break       if (turn == 1) break
  ...                        ...
➤
```

Peterson’s Algorithm

```
          flag[2] = {1, 1};   turn = 0;

  flag[0] = 1                 flag[1] = 1
  turn = 1                    turn = 0
  if (!flag[1]) break         if (!flag[0]) break
  if (turn == 0) break     ➤  if (turn == 1) break
  if (!flag[1]) break         if (!flag[0]) break
  if (turn == 0) break        if (turn == 1) break
  ...                         ...
➤
```

Peterson’s Algorithm

```
        flag[2] = {1, 1};   turn = 0;

  flag[0] = 1                 flag[1] = 1
  turn = 1                    turn = 0
  if (!flag[1]) break         if (!flag[0]) break
  if (turn == 0) break        if (turn == 1) break
  if (!flag[1]) break       ➤ if (!flag[0]) break
  if (turn == 0) break        if (turn == 1) break
  ...                         ...
➤
```

Peterson’s Algorithm

```
        flag[2] = {1, 1};   turn = 0;

  flag[0] = 1                 flag[1] = 1
  turn = 1                    turn = 0
  if (!flag[1]) break         if (!flag[0]) break
  if (turn == 0) break        if (turn == 1) break
  if (!flag[1]) break         if (!flag[0]) break
  if (turn == 0) break      ➤ if (turn == 1) break
  ...                         ...
➤
```

Peterson’s Algorithm

```
flag[2] = {0, 0};   turn = 0;
```

```
➤ flag[0] = 1
  turn = 1
  if (!flag[1]) break
  if (turn == 0) break
  if (!flag[1]) break
  if (turn == 0) break
  ...
```

```
➤ flag[1] = 1
  turn = 0
  if (!flag[0]) break
  if (turn == 1) break
  if (!flag[0]) break
  if (turn == 1) break
  ...
```

Peterson’s Algorithm

```
       flag[2] = {1, 0};   turn = 0;

  flag[0] = 1                ➤ flag[1] = 1
➤ turn = 1                     turn = 0
  if (!flag[1]) break          if (!flag[0]) break
  if (turn == 0) break         if (turn == 1) break
  if (!flag[1]) break          if (!flag[0]) break
  if (turn == 0) break         if (turn == 1) break
  ...                          ...
```

Peterson’s Algorithm

```
         flag[2] = {1, 1};   turn = 0;

  flag[0] = 1               flag[1] = 1
➤ turn = 1                ➤ turn = 0
  if (!flag[1]) break       if (!flag[0]) break
  if (turn == 0) break      if (turn == 1) break
  if (!flag[1]) break       if (!flag[0]) break
  if (turn == 0) break      if (turn == 1) break
  ...                       ...
```

Peterson’s Algorithm

```
flag[2] = {1, 1};   turn = 1;
```

```
  flag[0] = 1
  turn = 1
➤ if (!flag[1]) break
  if (turn == 0) break
  if (!flag[1]) break
  if (turn == 0) break
  ...
```

```
  flag[1] = 1
➤ turn = 0
  if (!flag[0]) break
  if (turn == 1) break
  if (!flag[0]) break
  if (turn == 1) break
  ...
```

Peterson’s Algorithm

```
        flag[2] = {1, 1};   turn = 0;

  flag[0] = 1               flag[1] = 1
  turn = 1                  turn = 0
➤ if (!flag[1]) break     ➤ if (!flag[0]) break
  if (turn == 0) break      if (turn == 1) break
  if (!flag[1]) break       if (!flag[0]) break
  if (turn == 0) break      if (turn == 1) break
  ...                       ...
```

Peterson’s Algorithm

```
       flag[2] = {1, 1};   turn = 0;

  flag[0] = 1                  flag[1] = 1
  turn = 1                     turn = 0
  if (!flag[1]) break        ➤ if (!flag[0]) break
➤ if (turn == 0) break         if (turn == 1) break
  if (!flag[1]) break          if (!flag[0]) break
  if (turn == 0) break         if (turn == 1) break
  ...                          ...
```

Peterson’s Algorithm

```
        flag[2] = {1, 1};   turn = 0;

  flag[0] = 1                flag[1] = 1
  turn = 1                   turn = 0
  if (!flag[1]) break        if (!flag[0]) break
➤ if (turn == 0) break     ➤ if (turn == 1) break
  if (!flag[1]) break        if (!flag[0]) break
  if (turn == 0) break       if (turn == 1) break
  ...                        ...
```

Peterson’s Algorithm

```
         flag[2] = {1, 1};   turn = 0;

  flag[0] = 1               flag[1] = 1
  turn = 1                  turn = 0
  if (!flag[1]) break       if (!flag[0]) break
  if (turn == 0) break    ➤ if (turn == 1) break
  if (!flag[1]) break       if (!flag[0]) break
  if (turn == 0) break      if (turn == 1) break
  ...                       ...
➤
```

Peterson’s Algorithm

```
        flag[2] = {1, 1};   turn = 0;

   flag[0] = 1                 flag[1] = 1
   turn = 1                    turn = 0
   if (!flag[1]) break         if (!flag[0]) break
   if (turn == 0) break        if (turn == 1) break
   if (!flag[1]) break       ➤ if (!flag[0]) break
   if (turn == 0) break        if (turn == 1) break
   ...                         ...
 ➤
```

Peterson’s Algorithm

```
        flag[2] = {1, 1};   turn = 0;

  flag[0] = 1                flag[1] = 1
  turn = 1                   turn = 0
  if (!flag[1]) break        if (!flag[0]) break
  if (turn == 0) break       if (turn == 1) break
  if (!flag[1]) break        if (!flag[0]) break
  if (turn == 0) break     ➤ if (turn == 1) break
  ...                        ...
➤
```

Peterson’s Algorithm

See **`count_peterson.c`**

Global Memory (not)

Peterson’s doesn’t work on a modern
multi-processor

- Each processor has its own local view of “global”
- Explicit synchronization actions also sync memory

Don’t bother trying things like

```
while (!is_ready);
```

A pure-C busy loop with no explicit synchronization (via a library) is practically never right

Hardware Support for Global Memory

x86: **`mfence`** instruction

More common: **`test-and-set`**

Also common: **`compare-and-swap`**

Compare and Swap

`int compare_and_swap(int *p, int orig, int new)`

- Sets **`*p`** to **`new`** if and only if the current value is **`orig`**
- Returns **`orig`** if set
- Returns **`new`** if not set

See **`count_cas.c`**

Reducing Memory Contention

See **`count_cas2.c`** and **`count4_cas.c`**

⇒ total time scales with number of processors

but total CPU use scales quadratically

Busy Waiting is Bad

When a thread busy-waits for something to happen, the OS doesn't know

Use OS-supplied synchronization constructs, instead

Mutex

One of the most primitive OS-supplied synchronization constructs is a ***mutex***

- **`mutex_lock(mutex_t *)`**
    - blocks thread if lock already held
- **`mutex_unlock(mutex_t *)`**

See **`count4_mutex.c`**

Indirect Synchronization

Other OS operations may imply synchronization

See **`count4_pipe.c`**