Concurrency Primitives

Synchronisation

Now we look at some other problems

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```
for (i = 0; i < 50; i++) {
    if (val[i] > 0)
        count1 = count1 + 1;
}
count = count1 + count2;
```

2

```
for (j = 50; j < 100; j++) {
    if (val[j] > 0)
        count2 = count2 + 1;
}
```

Now we look at some other problems

Consider our original counting code with a shared variable `count`. A simple solution might be to make `count` non-shared:

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for (i = 0; i < 50; i++) {
    if (val[i] > 0)
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count = count1 + count2;
```

2

```
for (j = 50; j < 100; j++) {
    if (val[j] > 0)
        count2 = count2 + 1;
}
```

There is now another, different, problem with this code!

Concurrency Primitives

Synchronisation

The problem now is *when is the* `count = count1 + count2` *executed?*

Concurrency Primitives

Synchronisation

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It will definitely happen after loop **1** has finished, but what about loop **2**?

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It will definitely happen after loop **1** has finished, but what about loop **2**?

We can’t rely (in a MIMD architecture) on the two loops on different cores running at the same time and finishing at the same time

Timings in the system may have the two loops running in any conceivable arrangement of before, after or overlapped

Concurrency Primitives

Synchronisation

1

```
for (i = 0; i < 50; i++) {
    if (val[i] > 0)
        count1 = count1 + 1;
}
count = count1 + count2;
```

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for (j = 50; j < 100; j++) {
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}
```

Concurrency Primitives

Synchronisation

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Another sequentialisation!

Concurrency Primitives

Synchronisation

More subtly: if this code is executed more than once (perhaps counting more than one array), thread **2** ought to wait for thread **1** before starting!

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It is possible that **1** is slow or paused for some reason, when **2** might do its bit and come around again on the next call to the count code, do the count on some other data, updating `count2` as it goes

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Finally **1** awakes and gets the wrong `count2`

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Synchronisation

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Finally **1** awakes and gets the wrong `count2`

This does happen and is a source of bugs

Concurrency Primitives

Semaphores

Semaphores can be used for thread synchronisation

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It can wait on a semaphore, again a simple flag, until another thread sets the flag. Then it knows it can continue

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Semaphores can be used for thread synchronisation

Typically, we might have some thread that can only continue its work when one (or more) others have finished doing something, maybe computing some inputs for the thread to process

It can wait on a semaphore, again a simple flag, until another thread sets the flag. Then it knows it can continue

Note that even though both locks and semaphores are flags, they are very different things! Beware it is common for people to confuse the two

Concurrency Primitives

Semaphores

Semaphores are manipulated by two atomic operations P and V that symbolically act atomically as:

```
P(s): while (s == 0) {
          suspend();
      }
      s = 0;
```

```
V(s):  s = 1;
       if any process waiting on s
          unblock one
```

Concurrency Primitives

Semaphores

On finding $s = 0$ a thread will suspend itself; when awoken it will re-attempt to set the semaphore: and it will often succeed, unless a third thread comes along and gets the semaphore first

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Other names for P are: wait, up, lock, enter, open

Other names for V are: signal, down, unlock, exit, close

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Other names for P are: wait, up, lock, enter, open

Other names for V are: signal, down, unlock, exit, close

P stands for “proberen”, V for “verhogen”, which are Dutch for “test” and “increase”

Concurrency Primitives

Semaphores

Semaphores synchronise across threads:

```
do something
wait(s)                 prepare data
read data               signal(s)
                        carry on
```

Thread 1 waits until thread 2 has prepared some data before reading it

Concurrency Primitives

Semaphores

Semaphores synchronise across threads:

```
                     prepare data
do something         signal(s)
wait(s)              carry on
read data
```

Thread 1 waits until thread 2 has prepared some data before reading it

The signal and wait might happen in any order

Concurrency Primitives

Counting Semaphores

The above are called *binary* semaphores as the idea can be trivially extended into *counting* semaphores

```
P(s): while (s == 0) {        V(s):  s = s + 1;
         suspend();                  if any process waiting on s
      }                                 unblock one
      s = s - 1;
```

Concurrency Primitives

Counting Semaphores

The above are called *binary* semaphores as the idea can be trivially extended into *counting* semaphores

```
P(s): while (s == 0) {        V(s):  s = s + 1;
          suspend();                 if any process waiting on s
      }                                 unblock one
      s = s - 1;
```

When initialised with the value *n*, this will allow *n* threads to open the semaphore before blocking

Concurrency Primitives

Counting Semaphores

This allows region access control when there can be one than one, but fewer than some limit in the region simultaneously

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For example, if there are 5 places at a dining table we can allow no more than 5 people in the room at a time

Concurrency Primitives

Counting Semaphores

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For example, if there are 5 places at a dining table we can allow no more than 5 people in the room at a time

Or 4 if they are philosophers…

Concurrency Primitives

Semaphores

Mutual exclusion with semaphores happens to be easy:

```
wait(s);
<CR>
signal(s);
```

Wait for the semaphore; signal it's free when you are done

Concurrency Primitives

Semaphores

Mutual exclusion with semaphores happens to be easy:

```
wait(s);
<CR>
signal(s);
```

Wait for the semaphore; signal it's free when you are done

But don't do this: it's better to use locks here. Semaphores are more general than locks: they allow a thread to suspend itself and be awoken by another thread when some condition is true

Concurrency Primitives

Semaphores

Mutexes: the thread that sets the flag must be the thread that clears the flag

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Semaphores should be used *across* threads, mutexes must not

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Semaphores: the thread that sets the flag will generally be different from the thread that clears the flag

Semaphores should be used *across* threads, mutexes must not

The locking effect is in some sense incidental: more useful is using semaphores to synchronise

Concurrency Primitives

POSIX Semaphores

POSIX semaphores:

```
#include <semaphore.h>
sem_t sem;
int sem_init(sem_t *sem, int pshared, unsigned int value);
int sem_destroy(sem_t *sem);
int sem_wait(sem_t *sem);
int sem_post(sem_t *sem);
int sem_trywait(sem_t *sem);
```

“post” for signal

Exercise Add a semaphore to the `count1/count2` example to get thread 1 to wait for thread 2 before doing the final sum

Exercise Then add another semaphore to get thread 2 to wait for thread 1 before starting

Concurrency Primitives

Barriers

Another synchronisation primitive is *barriers* (occasionally called *rendezvous)*

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A barrier stops threads from continuing until some required number of threads have all hit the barrier; then they can all continue together

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Another synchronisation primitive is *barriers* (occasionally called *rendezvous)*

A barrier stops threads from continuing until some required number of threads have all hit the barrier; then they can all continue together

This allows us to synchronise parts of the program: recall supersteps

Concurrency Primitives

Barriers

Suppose we have a list of numbers we want to square then add in pairs

```
for (i = 0; i < 100; i++) {
    v[i] = v[i]*v[i];
}
for (i = 0; i < 100; i++) {
    s[i] = v[i] + v[99-i];
}
```

Concurrency Primitives

Barriers

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```
for (i = 0; i < 100; i++) {
    v[i] = v[i]*v[i];
}
for (i = 0; i < 100; i++) {
    s[i] = v[i] + v[99-i];
}
```

We can parallelise this by having (say) 4 threads; each thread squares a block of values; then they add a block of values

Concurrency Primitives

Barriers

1	2	3	4
v[0]^2	v[25]^2	v[50]^2	v[75]^2
v[1]^2	v[26]^2	v[51]^2	v[76]^2
v[2]^2	v[27]^2	v[52]^2	v[77]^2
...	...	...	...
v[24]^2	v[49]^2	v[74]^2	v[99]^2
v[0]+v[99]	v[25]+v[74]	v[50]+v[49]	v[75]+v[24]
v[1]+v[98]	v[26]+v[73]	v[51]+v[48]	v[76]+v[25]
...	...	...	...
v[24]+v[75]	v[49]+v[50]	v[74]+v[25]	v[99]+v[0]

Concurrency Primitives

Barriers

```
1                                2                                3...
for (i = 0; i < 25; i++) {       for (j = 25; j < 50; j++) {
    v[i] = v[i]*v[i];                v[j] = v[j]*v[j];
}                                }
for (i = 0; i < 25; i++) {       for (j = 25; j < 50; j++) {      ...
    s[i] = v[i] + v[99-i];           s[j] = v[j] + v[99-j];
}                                }
```

Concurrency Primitives

Barriers

```
1                             2                             3...
for (i = 0; i < 25; i++) {  for (j = 25; j < 50; j++) {
    v[i] = v[i]*v[i];           v[j] = v[j]*v[j];
}                             }
for (i = 0; i < 25; i++) {  for (j = 25; j < 50; j++) {       ...
    s[i] = v[i] + v[99-i];      s[j] = v[j] + v[99-j];
}                             }
```

Again, the above might work sometimes, or many times, but it is buggy

Concurrency Primitives

Barriers

The problem here is again that the threads may not all be running at the same speed: perhaps one thread is interrupted and descheduled by the OS; or memory access is not uniform speed; or many other factors

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So we can’t rely on all the threads finishing their squares at precisely the same time: one thread might finish its block and start adding using values not yet finished squaring

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So we can’t rely on all the threads finishing their squares at precisely the same time: one thread might finish its block and start adding using values not yet finished squaring

Another synchronisation problem

Concurrency Primitives

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v[1]^2	v[26]^2	v[51]^2	
v[2]^2	v[27]^2	v[52]^2	v[75]^2
...	...	...	v[76]^2
...	...	...	...
v[24]^2	v[49]^2	v[74]^2	v[97]^2
v[0]+ **v[99]**	v[25]+v[74]	v[50]+v[49]	v[98]^2
v[1]+v[98]	v[26]+v[73]	v[51]+v[48]	**v[99]^2**
...	...	...	v[75]+v[24]
...	...	...	...
v[24]+v[75]	v[49]+v[50]	v[74]+v[25]	v[97]+v[2]
			v[98]+v[1]
			v[99]+v[0]

Concurrency Primitives

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...	...	...	v[75]+v[24]
...	...	...	...
v[24]+v[75]	v[49]+v[50]	v[74]+v[25]	v[97]+v[2]
			v[98]+v[1]
			v[99]+v[0]

This is how we get the wrong answer: again just because the lines of code for the adds follows the lines of code for the squares make us believe every add happens after every square

Concurrency Primitives

Barriers

We need to synchronise all the threads at the end of the squares before allowing them to continue with the adds

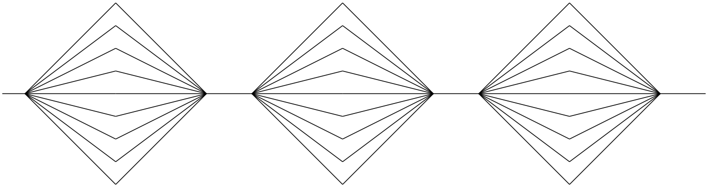
```
                     b = make_barrier(4);
<parallel squares> <parallel squares> <parallel squares> ...
barrier_wait(b);   barrier_wait(b);   barrier_wait(b);   ...
<parallel adds>    <parallel adds>    <parallel adds>    ...
```

Only when all 4 threads have reached the barrier can they all proceed

Concurrency Primitives

Barriers

Barriers are good for the superstep style of programming



Supersteps

Concurrency Primitives

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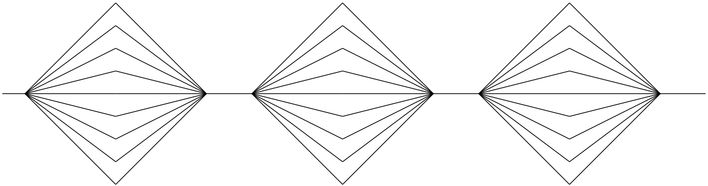

Supersteps

But beware: as a barrier synchronises many threads, there is potentially a lot of waiting going on: we can't progress faster than the slowest thread

Concurrency Primitives

Barriers

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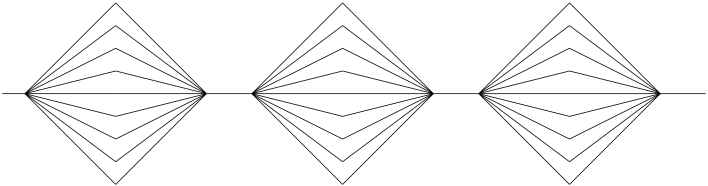

Supersteps

But beware: as a barrier synchronises many threads, there is potentially a lot of waiting going on: we can't progress faster than the slowest thread

Thus barriers are best when all the threads are doing roughly the same amount of work

Concurrency Primitives

POSIX Barriers

```
#include <pthread.h>
pthread_barrier_t barrier;
int pthread_barrier_init(
    pthread_barrier_t *restrict barrier,
    const pthread_barrierattr_t *restrict attr,
    unsigned count);
int pthread_barrier_destroy(pthread_barrier_t *barrier);
int pthread_barrier_wait(pthread_barrier_t *barrier);
```

A barrier can be reused immediately after it has released its threads; it has a fixed value of *n* set when it is initialised

Concurrency Primitives

POSIX Barriers

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#include <pthread.h>
pthread_barrier_t barrier;
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```

A barrier can be reused immediately after it has released its threads; it has a fixed value of *n* set when it is initialised

Exercise Have a look at the return value from `pthread_barrier_wait`

Exercise Fix the `count1/count2` problem with barriers

Exercise Both semaphores and barriers are about synchronisation. Think about how you might implement barriers using semaphores

Exercise Think about how you might implement semaphores using barriers

Concurrency Primitives

Condition Variables

One last primitive we are going to look at is *condition variables*

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The idea is that one or more threads can wait on a condition variable until another signals that the required condition is now true

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As the name suggests, it is a way a thread can wait until some condition is true

The idea is that one or more threads can wait on a condition variable until another signals that the required condition is now true

The signal can either let just *one* thread continue, or be a *broadcast* that lets all waiting threads continue

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As the name suggests, it is a way a thread can wait until some condition is true

The idea is that one or more threads can wait on a condition variable until another signals that the required condition is now true

The signal can either let just *one* thread continue, or be a *broadcast* that lets all waiting threads continue

Condition variables are normally associated with a mutex, and are used *inside* a critical region protected by that mutex

Concurrency Primitives

Condition Variables

1

```
get_lock(mx);
<CR>
condvar_wait(cv, mx);
(wait)
<CR>
free_lock(mx);
```

2

```
get_lock(mx);
<CR>
condvar_signal(cv);
free_lock(mx);
```

`condvar_wait` releases the mutex and waits on the condition variable

Concurrency Primitives

Condition Variables

1

```
get_lock(mx);
<CR>
condvar_wait(cv, mx);
(wait)
<CR>
free_lock(mx);
```

2

```
get_lock(mx);
<CR>
condvar_signal(cv);
free_lock(mx);
```

`condvar_wait` releases the mutex and waits on the condition variable

When the other thread signal signals and releases the mutex, the first thread regains the mutex and continues within the critical region

Concurrency Primitives

Condition Variables

The condition variable allows thread 1 to “step outside” the critical region, letting another thread to enter and do something

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With a `broadcast` all other threads are marked as ready to run, but only one will regain the lock; the others will blocked on the lock as normal

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Conditions variables combine mutual exclusion and synchronisation

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With a `broadcast` all other threads are marked as ready to run, but only one will regain the lock; the others will blocked on the lock as normal

One will get the lock when the first thread releases it; and so on

Concurrency Primitives

POSIX Condition Variables

```
#include <pthread.h>
int pthread_cond_init(pthread_cond_t *restrict cond,
           const pthread_condattr_t *restrict attr);
int pthread_cond_destroy(pthread_cond_t *cond);
int pthread_cond_wait(pthread_cond_t *restrict cond,
           pthread_mutex_t *restrict mutex);
int pthread_cond_timedwait(pthread_cond_t *restrict cond,
           pthread_mutex_t *restrict mutex,
           const struct timespec *restrict abstime);
int pthread_cond_signal(pthread_cond_t *cond);
int pthread_cond_broadcast(pthread_cond_t *cond);
```

Concurrency Primitives

POSIX Condition Variables

As an example of the kind of grungy detail that parallelism has to address: POSIX recognises that there is a nasty implementation detail that would otherwise make implementing condition variables impractical

Concurrency Primitives

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The specification for `pthread_cond_signal` says

> *The* `pthread_cond_signal()` *function shall unblock at least one of the threads that are blocked on the specified condition variable* `cond`

Concurrency Primitives

POSIX Condition Variables

As an example of the kind of grungy detail that parallelism has to address: POSIX recognises that there is a nasty implementation detail that would otherwise make implementing condition variables impractical

The specification for `pthread_cond_signal` says

> *The* `pthread_cond_signal()` *function shall unblock at least one of the threads that are blocked on the specified condition variable* `cond`

"at *least* one": there is a (rare) problem of *spurious wakeups* that is in general too expensive to avoid

Concurrency Primitives

POSIX Condition Variables

This just means you have to be a bit formulaic about the use of condition variables and always have a *condition* to test before continuing

1

```
iteration = 0;
get_lock(mx);
<CR>
it = iteration;
while (it == iteration)
    condvar_wait(cv, mx);
<CR>
free_lock(mx);
```

2

```

get_lock(mx);
<CR>
iteration++;
condvar_signal(cv, mx);
free_lock(mx);
```

Thread 1 might get awoken spuriously but it doesn’t want to continue until the next iteration

Concurrency Primitives

POSIX Condition Variables

In general you would test for whatever condition you were waiting for: thread 2 sets the condition, thread 1 should test for it

Concurrency Primitives

POSIX Condition Variables

In general you would test for whatever condition you were waiting for: thread 2 sets the condition, thread 1 should test for it

Condition variables are very useful, but a bit of a pain to use

We have called these things *primitives*, but we can implement them in terms of each other

Concurrency Primitives

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Exercise Do this

Concurrency Primitives

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"Primitive" is actually a good description as they are all very low level

Concurrency Primitives

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(b) the time spent in executing the code of the primitive

Note part (a) isn't really a limitation of the primitive: it's necessary if it is to work at all. It is (b) that the implementation of a primitive seeks to minimise

Concurrency Control

Higher Level

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These come in many forms

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We shall be looking at all of these approaches

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So code needs to be rewritten to make best advantage of parallelism

The hope (and economics) is we can take existing code using an existing language and modify it

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The easiest way is to leave the language itself untouched, just adding a library of functions that do parallelism

For example, the POSIX `pthread` approach

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Libraries

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But you can’t just add a parallel library to a sequential language and hope everything is OK

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Threads again

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And some hardware optimisations can break parallel code

Concurrency Control

Compiler Reordering

Modern compilers often reorder code to make things more efficient

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For example, main memory access is (relatively) slow, so if the value of a variable is needed, the compiler might try to start loading it earlier than the code might suggest

Concurrency Control

Compiler Reordering

Given code

```
y = 2;
x = z;
x += y; // need to wait for z before we can do this
```

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The effect is the same, but it goes a little faster. The compiler in effect rewrites your code

Concurrency Control

Compiler Reordering

This could break things. Consider

A
```
while (cont == 0) {/* nothing */}
print x;
```

B
```
x = 42;
cont = 1;
```

where the intent was to have thread A to wait for thread B to set the `cont` flag before continuing to print 42

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Compiler Reordering

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```
A                                           B
while (cont == 0) {/* nothing */}           x = 42;
print x;                                    cont = 1;
```

where the intent was to have thread A to wait for thread B to set the `cont` flag before continuing to print 42

A compiler only seeing the code for B may conclude that the variables `cont` and `x` are independent and so (perhaps for whatever reason) it can rearrange the code as

```
cont = 1;
x = 42;
```

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Similarly for A: it is possible that the read of `x` can done before the loop

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Note: *never* write code like this in the hope that it might work: it is simply buggy code! Use a semaphore or equivalent

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Note: *never* write code like this in the hope that it might work: it is simply buggy code! Use a semaphore or equivalent

The problem is that there is a hidden relationship between the variables `x` and `cont` that is in the mind of the programmer, but is not expressed in the code

Concurrency Control

Compiler Reordering

Example. Consider the code:

```
int a = 0;
int b = 0;
```

```
A
a = 42;
printf("%d\n", b);
```

```
B
b = 42;
printf("%d\n", a);
```

Explain how it might print `0` twice, even though it appears we always print after an update