CSE502: Foundations of Parallel Programming

Lecture 11: Mutual Exclusion in async-finish Program

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Recap (1/2)

- Loop level parallelism

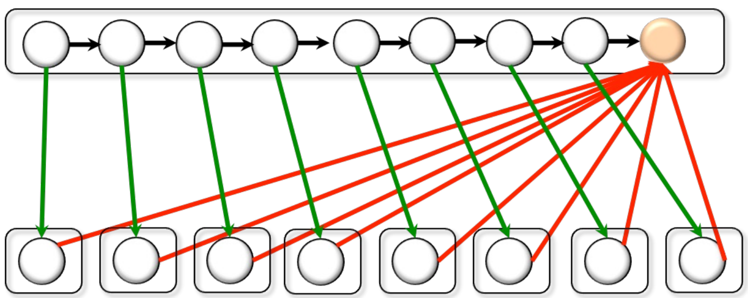
```
void foo() {
  loop_domain_t loop = {0, 8, 1, 1};
  finish([&]() {
    forasync1D (&loop, [=](int i) {
      S(i); // can execute in parallel for all i
    }, MODE_TYPE);
  });
}
```

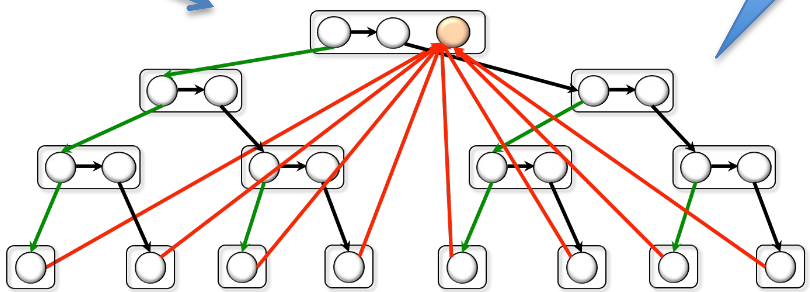
High productivity

Avoids deque overflow

Multiple producer
Multiple consumer
(faster task diffusion)

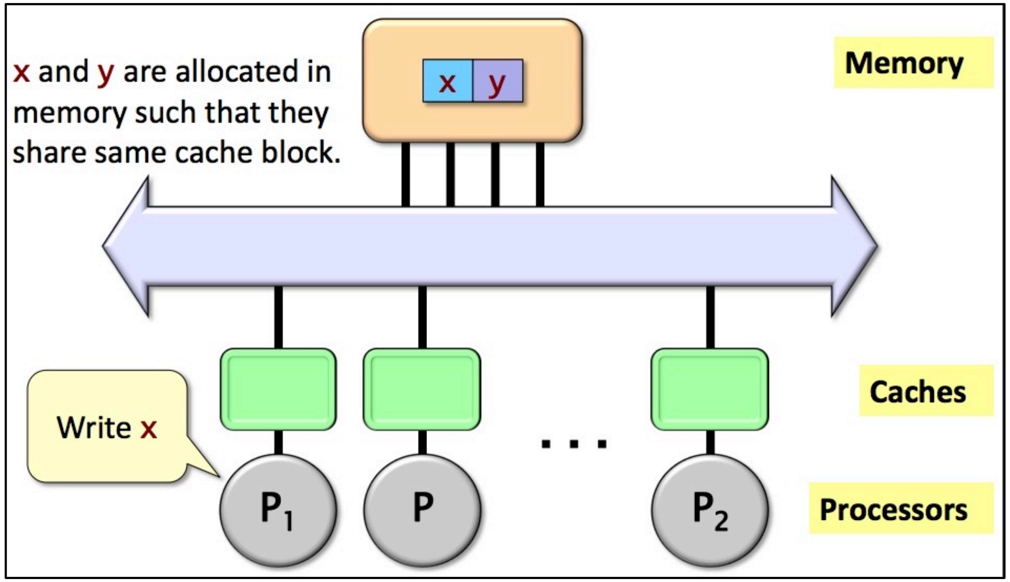
Smaller CPL

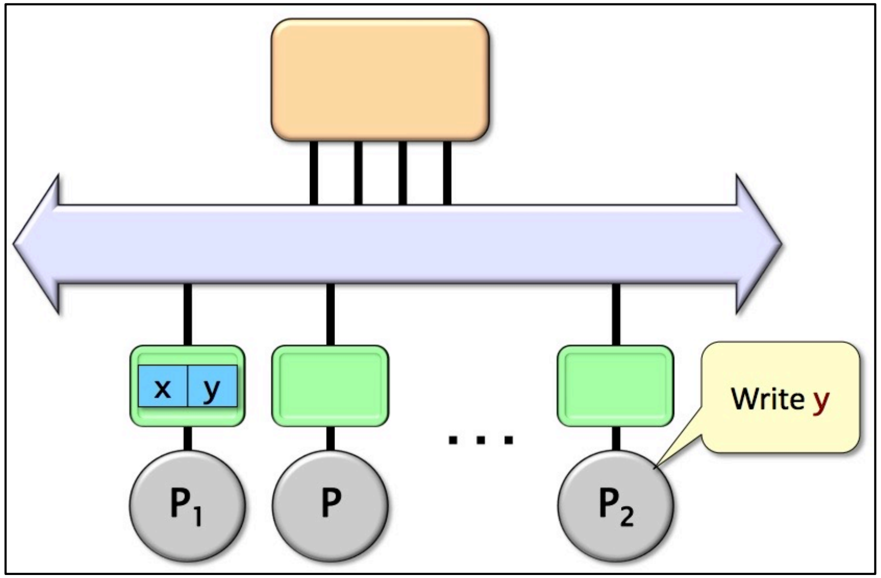


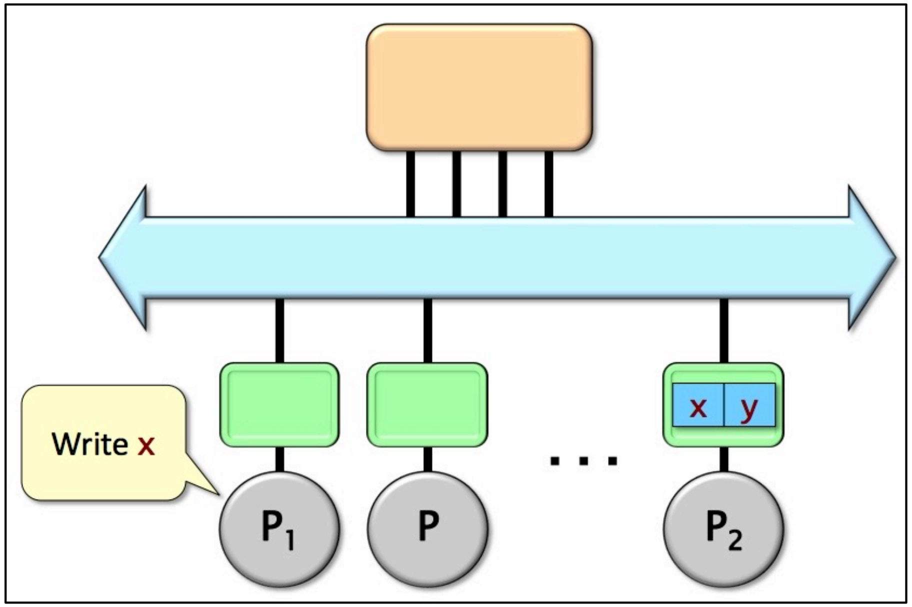


Recap (2/2)

- False sharing

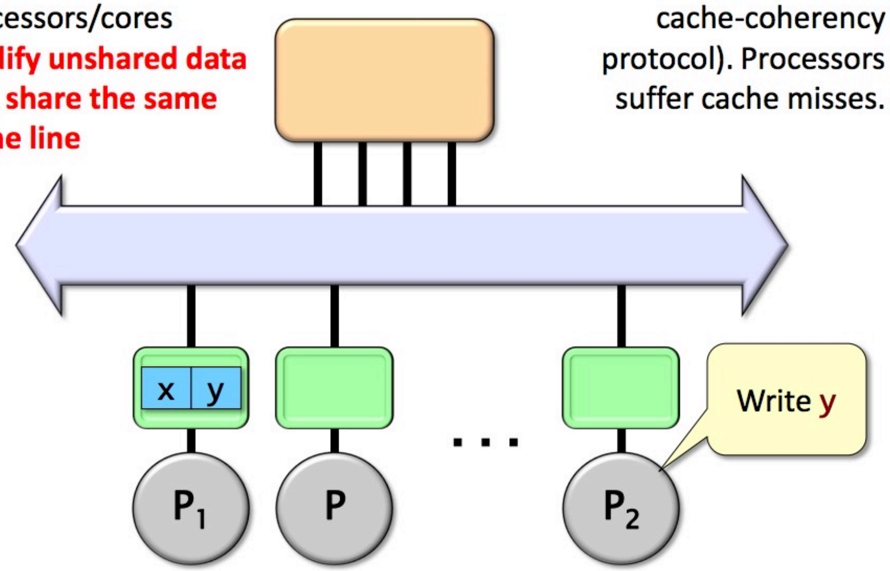






False sharing: threads running on different processors/cores **modify unshared data** that **share the same cache line**

Ping-pong effect on cache-line (due to cache-coherency protocol). Processors suffer cache misses.



Today's Class

- Mutual exclusion in async-finish program

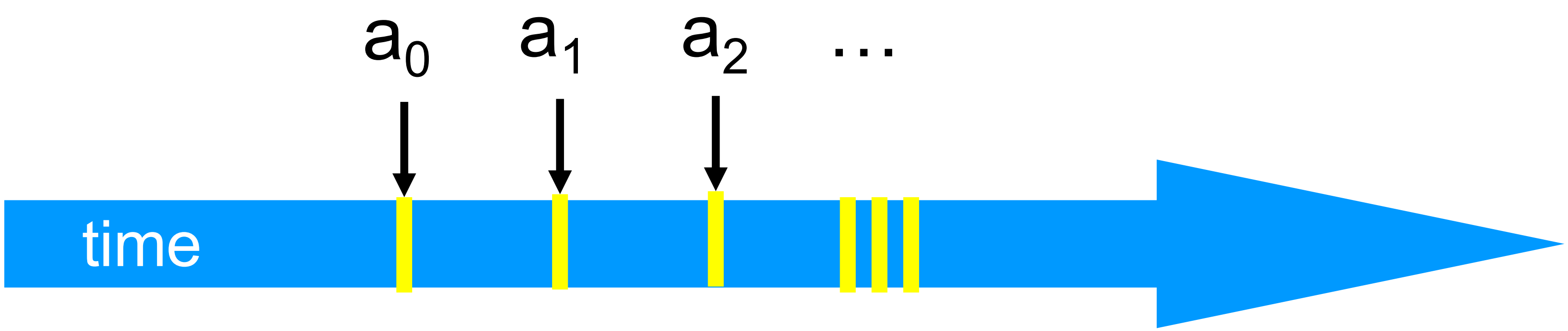
Mutual Exclusion

- ***Critical section:*** a block of code that access shared modifiable data or resource that should be operated on by only one thread at a time.
- ***Mutual exclusion:*** a property that ensures that a critical section is only executed by a thread at a time.
  - *Otherwise it results in a race condition!*

Acknowledgement: Slides adopted from the companion slides for the book "The Art of Multiprocessor Programming" by Maurice Herlihy and Nir Shavit

Threads

- A ***thread*** A is (formally) a sequence a_0, a_1, ... of events
  - Notation: $a_0 \rightarrow a_1$ indicates order



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Example Thread Events

- Assign to shared variable
- Assign to local variable
- Invoke method
- Return from method
- Lots of other things …

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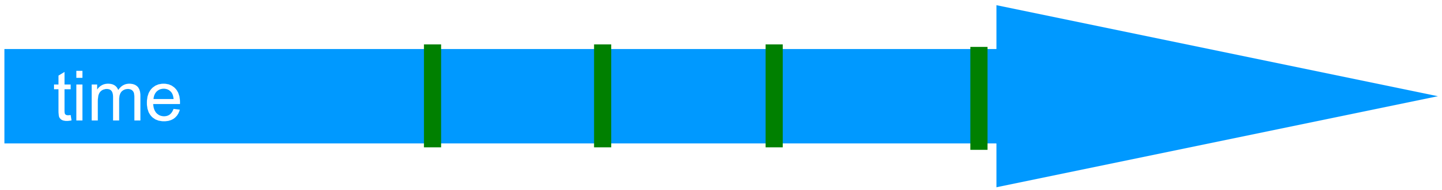
Concurrency

- Thread A

- Thread B



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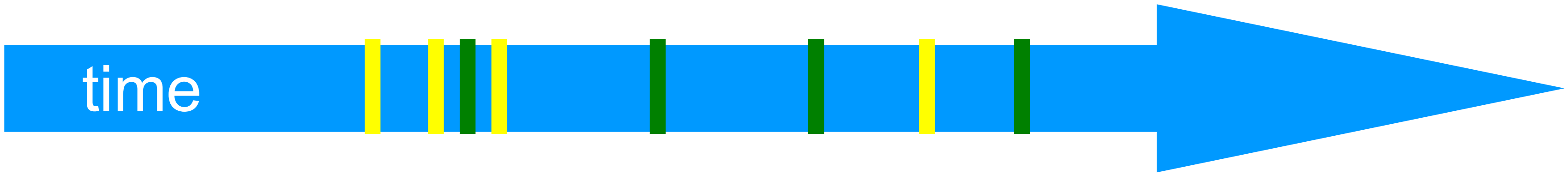
Interleavings

- Events of two or more threads
  - Interleaved
  - Not necessarily independent (why?)



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What we Learned in Lecture 06

- We saw two different cases of data-races using the examples of parallel ArraySum and parallel MatrixMultiplication. We were able to resolve these data-races by correct placements of async and finish
- However, there are many cases in practice when two tasks legitimately need to perform conflicting accesses to shared locations without incurring data-races

Incrementing Pointer Content in Parallel

```
void increment(uint64_t* pointer, uint64_t iterations) {
  loop_domain_t loop = {0, iterations, 1, 1 };
  finish ([&]() {
    forasync1D(&loop, [=](uint64_t i) {

      *pointer += 1;

    }, FORASYNC_MODE_RECURSIVE);
  });
}
```

Critical Section

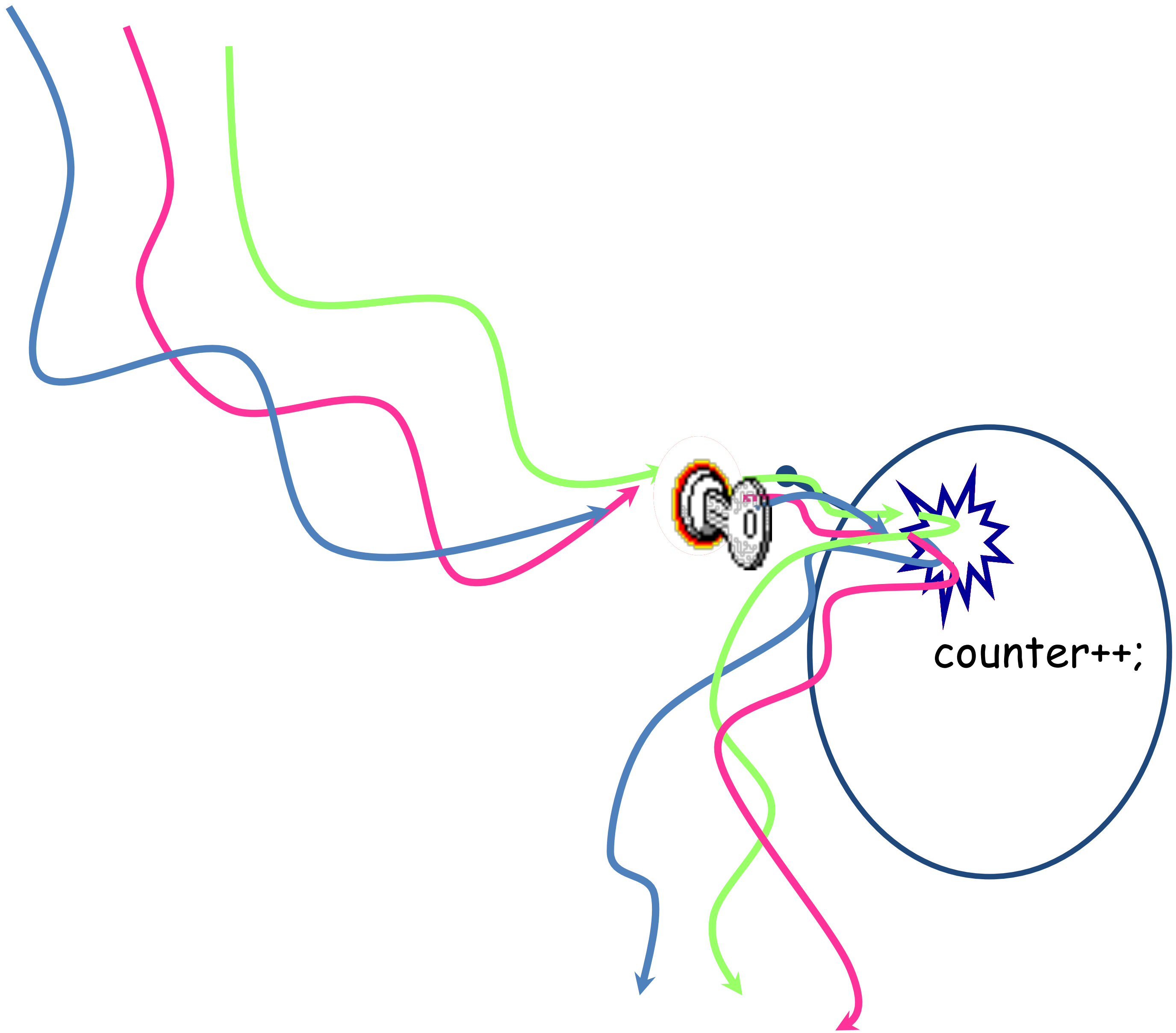
Incrementing Pointer Content in Parallel

```
void increment(uint64_t* pointer, uint64_t iterations) {
  loop_domain_t loop = {0, iterations, 1, 1 };
  finish ([&]() {
    forasync1D(&loop, [=](uint64_t i) {
      pthread_mutex_lock(&mutex);
      *pointer += 1;
      pthread_mutex_unlock(&mutex);
    }, FORASYNC_MODE_RECURSIVE);
  });
}
```

Critical Section

One way to resolve this data-race is by using a mutex lock

Analyzing our Counter Increment Example



- Only one thread can get the “key” to enter the critical section
- Rest all threads will be queued to get the lock

Properties of a Good Locking Algorithm

- Safety guarantee
  – Mutual exclusion
- Progress guarantee
  – Deadlock freedom
  – Starvation freedom

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Properties of a Good Locking Algorithm

- Mutual exclusion
- ***Deadlock freedom:*** *system as a whole makes progress.*
  If some thread calls **lock()** and never returns, then other threads must complete **lock()** and **unlock()** calls infinitely often.
- Starvation freedom

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Properties of a Good Locking Algorithm

- Mutual exclusion
- ***Deadlock freedom:*** *system as a whole makes progress.*
  If some thread calls **lock()** and never returns, then other threads must complete **lock()** and **unlock()** calls infinitely often.
- ***Starvation freedom:*** A thread should not indefinitely hold the lock for doing some big computation while other threads keep waiting to get this lock

Acknowledgement: Slides adopted from the companion slides for the book "The Art of Multiprocessor Programming" by Mauric● Herlihy and Nir Shavit

isolated Construct in HClib

```
isolated([&]( ) { S; });
```

- Isolated construct identifies a critical section
  - Introduced by Habanero-Java that also has a very mature implementation of isolated
  - *HClib currently has an experimental implementation of isolated*
- Two tasks executing isolated constructs are guaranteed to perform them in mutual exclusion
  - Isolation guarantee applies to (isolated, isolated) pairs of constructs, not to (isolated, non-isolated) pairs of constructs
- No parallelism constructs inside isolated
  - E.g., if async is spawned then isolation guarantee will only apply to the creation of async, not to its execution
- Isolated constructs can never cause a deadlock
  - Other techniques used to enforce mutual exclusion (e.g., locks) can lead to a deadlock, if used incorrectly

Source: https://wiki.rice.edu/confluence/download/attachments/24426821/comp322-s16-lec20-slides-v1.key.pdf?version=1&modificationDate=1483206145246&api=v2

Use of isolated to Fix the Previous Conflicting Access

```
void increment(uint64_t* pointer, uint64_t iterations) {
  loop_domain_t loop = {0, iterations, 1, 1 };
  finish ([&]() {
    forasync1D(&loop, [=](uint64_t i) {
      isolated([=]() {
        *pointer += 1;
      });
    }, FORASYNC_MODE_RECURSIVE);
  });
}
```

Critical Section

Code available on github: https://github.com/vivkumar/cse502/blob/master/hclib/test/lec12/

Lets take Another Example: Fibonacci Reducer

```
uint64_t result = 0;
void fib(uint64_t n) {
  if(n < THRESHOLD) {
      uint64_t value = fib_sequential(n);

      result += value;

  }
  else {
    async([=]() {
      fib(n-1);
    });
    fib(n-2);
  }
}

int main(int argc, char** argv) {
  finish ([=]() {
    fib(n);
  });
  printf("Fib(%" PRIu64 ") is %" PRIu64 "\n",n, result);
}
```

Is this Correct ?

Lets take Another Example: Fibonacci Reducer

Code available on github: https://github.com/vivkumar/cse502/blob/master/hclib/test/lec12/

```
uint64_t result = 0;
void fib(uint64_t n) {
  if(n < THRESHOLD) {
      uint64_t value = fib_sequential(n);
      isolated([=]() {
      result += value;
      });
  }
  else {
    async([=]() {
      fib(n-1);
    });
    fib(n-2);
  }
}

int main(int argc, char** argv) {
  finish ([=]() {
    fib(n);
  });
  printf("Fib(%" PRIu64 ") is %" PRIu64 "\n",n, result);
}
```

Critical Section

Is that Enough ??

```
void increment(uint64_t* pointer, uint64_t iterations) {
  loop_domain_t loop = {0, iterations, 1, 1 };
  finish ([&]() {
    forasync1D(&loop, [=](uint64_t i) {
      isolated([=]() {
        *pointer += 1;
      });
    }, FORASYNC_MODE_RECURSIVE);
  });
}
```

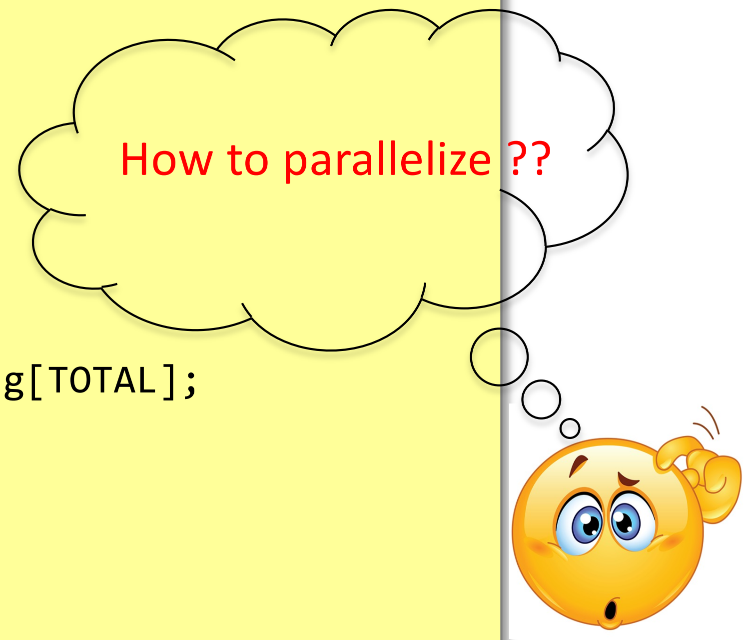
Critical Section

This seems like it is just a syntactic sugar to replace pthread_mutex_lock and pthread_mutex_unlock ?
What is so special about isolated ?

Code available on github: https://github.com/vivkumar/cse502/blob/master/hclib/test/lec12/

Lets Take the Example of Transferring $$ from One Account to Another

```
class Account {
  double balance;
  void debit(double amount);
  void credit(double amount);
};
class Transfer {
  Account source, destination;
  double amount;
  void run() {
    source.debit(amount);
    destination.credit(amount);
  }
};
class Bank {
  void fund_transfer() {
    Accounts numAccounts[N];Transfer pending[TOTAL];
    for(uint64_t i=0; i<TOTAL; i++) {
      pending[i].run();
    }
  }
};
```



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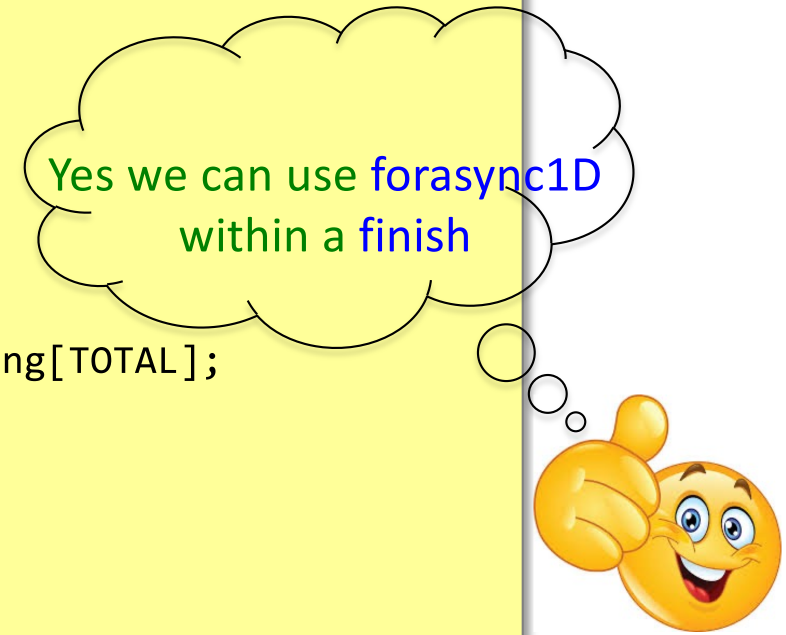
class Bank {
  void fund_transfer() {
    Accounts numAccounts[N];Transfer pending[TOTAL];
    loop_domain_t loop = {0, TOTAL, 1, 1};
    finish([&]() {
      foasync1D([=](uint64_t i) {
        pending[i].run();
      }, FORASYNC_MODE_RECURSIVE);
    });
  }
};
```



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  double balance;
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};
class Transfer {
  Account source, destination;
  double amount;
  void run() {
    source.debit(amount);
    destination.credit(amount);
  }
};
class Bank {
  void fund_transfer() {
    Accounts numAccounts[N];Transfer pending[TOTAL];
    loop_domain_t loop = {0, TOTAL, 1, 1};
    finish([&]() {
      foasync1D([=](uint64_t i) {
        pending[i].run();
      }, FORASYNC_MODE_RECURSIVE);
    });
  }
};
```

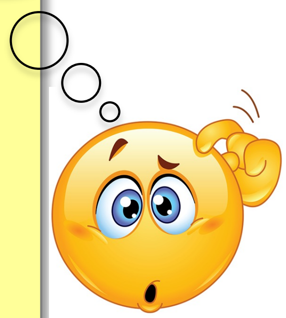
Is this Correct ??

Data-race!!

Lets Take the Example of Transferring $$ from One Account to Another

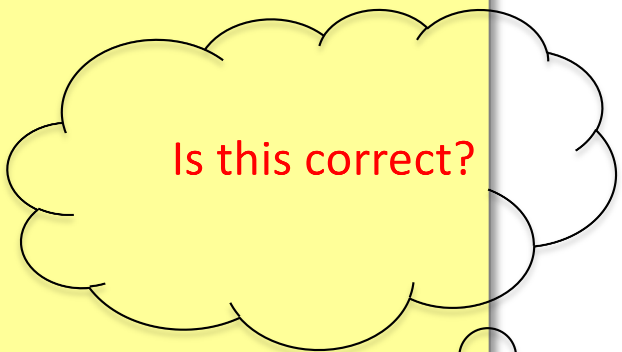
```
class Account {
  double balance;
  void debit(double amount);
  void credit(double amount);
};
class Transfer {
  Account source, destination;
  double amount;
  void run() {
    isolated([&]() {
    source.debit(amount);
    destination.credit(amount);
    });
  }
};
class Bank {
  void fund_transfer() {
    Accounts numAccounts[N];Transfer pending[TOTAL];
    loop_domain_t loop = {0, TOTAL, 1, 1};
    finish([&]() {
      foasync1D([=](uint64_t i) {
        pending[i].run();
      }, FORASYNC_MODE_RECURSIVE);
    });
  }
};
```

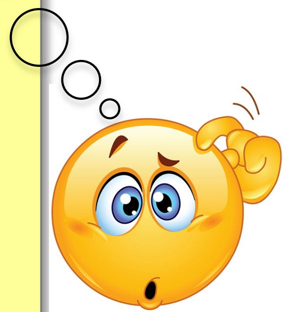
Do we still have the parallelism?



Lets Take the Example of Transferring $$ from One Account to Another

```
class Account {
  double balance;
  void debit(double amount);
  void credit(double amount);
};
class Transfer {
  Account source, destination;
  double amount;
  void run() {
    lock(&source); lock(&destination)
    source.debit(amount);
    destination.credit(amount);
    unlock(&destination); unlock(&source)
  }
};
class Bank {
  void fund_transfer() {
    Accounts numAccounts[N];Transfer pending[TOTAL];
    loop_domain_t loop = {0, TOTAL, 1, 1};
    finish([&]() {
      foasync1D([=](uint64_t i) {
        pending[i].run();
      }, FORASYNC_MODE_RECURSIVE);
    });
  }
};
```






DEADLOCK
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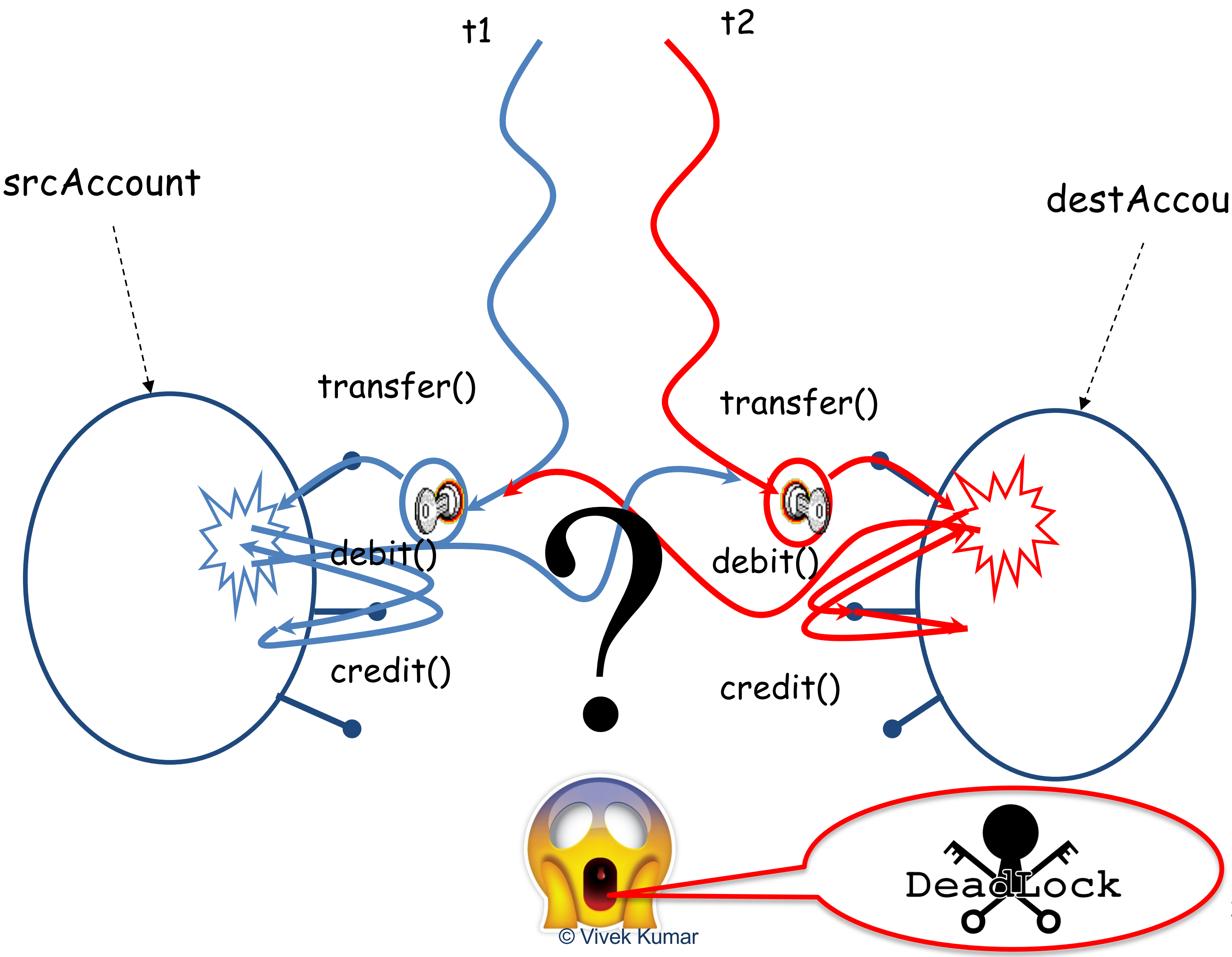
Let's Analyze Our Bank Transaction



Deadlock Avoidance

- **Deadlock occurs when multiple threads need the same locks but obtain them in different order**
- Not so easy to avoid deadlocks
- It's an active research area

Let's try simple remedies to fix
our Bank Transaction program

Deadlock Avoidance

- Lock ordering
  - Ensure that all locks are taken in same order by any thread
- Lock timeout
  - Put a timeout on lock attempts
    - pthread_mutex_timedlock

Object Based Isolation for Avoiding Deadlock in async-finish Program

isolated(obj1, obj2, …, lambda_function)

- In this case, programmer specifies list of objects for which isolation is required
- Mutual exclusion is only guaranteed for instances of isolated constructs that have a common object in their object lists
  - Standard isolated is equivalent to "isolated(*)" by default i.e., isolation across all objects
- Experimental implementation exists in HClib (some APIs might change in future but not the concepts)

Lets Take the Example of Transferring $$ from One Account to Another

```
class Account {
  double balance;
  void debit(double amount);
  void credit(double amount);
};
class Transfer {
  Account source, destination;
  double amount;
  void run() {
    isolated(&source, &destination, [&]() {
      source.debit(amount);
      destination.credit(amount);
    });
  }
};
class Bank {
  void fund_transfer() {
    Accounts numAccounts[N];Transfer pending[TOTAL];
    loop_domain_t loop = {0, TOTAL, 1, 1};
    enable_isolation_n(numAccounts, N);
    finish([&]() {
      foasync1D([=](uint64_t i) {
        pending[i].run();
      }, FORASYNC_MODE_RECURSIVE);
    });
    disable_isolation_n(numAccounts, N);
  }
};
```

Note: This will never deadlock. You can have objects in any order

Experimental support, hence outside of finish. In future you may not even need these two API..

Code available on github: https://github.com/vivkumar/cse502/blob/master/hclib/test/lec12/

Implementation of Object Based Isolation

- `enable_isolation_n(numAccounts, N);`
  - Runtime will add these objects in a hashmap
  - Every object is associated with a unique **uint64_t** **counter** and a lock
- `isolated(&source, &destination, lambda);`
  - Runtime will get these objects from the hashmap and then sort them using the value of their **counter**
  - Lock is then acquired on each object in the ascending (or descending) value of the their **counter**
  - User provided critical section is executed and then each of these objects are unlocked (in same order)
  - This technique avoids the deadlock
- `disable_isolation_n(numAccounts, N);`
  - Remove these objects from the hashmap

Pros and Cons of Object Based Isolation

- Pros
  - Productivity: simpler approach than “locks”
  - Deadlock-freedom property is guaranteed
- Cons
  - Programmer needs to worry about getting the object list right
  - Objects in object list can only be specified at start of the isolated construct (new objects cannot be added later on)

Source: https://wiki.rice.edu/confluence/download/attachments/24426821/comp322-s16-lec20-slides-v1.key.pdf?version=1&modificationDate=1483206145246&api=v2

Next Class

- Mid semester review