Once again, our example

```
def T1():
    amount -= 10000
    done1 = True

def T2():
    amount /= 2
    done2 = True
```

Once again, our example

```
def T1():
    amount −= 10000
    done1 = True

def T2():
    amount /= 2
    done2 = True

def main():
    await done1 and done2
    assert (amount == 40000) or (amount == 45000), amount

done1 = done2 = False
amount = 100000
spawn T1()
spawn T2()
spawn main()
```

Once again, our example

```
def T1():
    amount −= 10000
    done1 = True

def T2():
    amount /= 2
    done2 = True

def main():
    await done1 and done2
    assert (amount == 40000) or (amount == 45000), amount

done1 = done2 = False
amount = 100000
spawn T1()
spawn T2()
spawn main()
```

Equivalent to:

```
while not (done1 and done 2):
    pass
```

Once again, our example

```
def T1():
    amount −= 10000
    done1 = True

def T2():
    amount /= 2
    done2 = True

def main():
    await done1 and done2
    assert (amount == 40000) or (amount == 45000), amount

done1 = done2 = False
amount = 100000
spawn T1()
spawn T2()
spawn main()
```

Assertion: useful to check properties

Once again, our example

```
def T1():
    amount −= 10000
    done1 = True

def T2():
    amount /= 2
    done2 = True

def main():
    await done1 and done2
    assert (amount == 40000) or (amount == 45000), amount

done1 = done2 = False
amount = 100000
spawn T1()
spawn T2()
spawn main()
```

Output amount if assertion fails

An important note on assertions

- An assertion is not part of your algorithm
- Semantically an assertion is a no-op
  - it is never expected to fail because it is supposed to state a fact

That said…

- Assertions are super-useful
  - $\boxed{\text{@label: assert P}}$ is a type of invariant:
    - $pc = label \Rightarrow P$
- Use them liberally
  - in C, Java, …, they are automatically removed in production code — or automatically optimized out if you have a really good compiler
- They are great for testing
- They are executable documentation
  - comments tend to get outdated over time

That said…

- Comment them out before submitting a programming assignment
  - you don't want your assertions to fail while we are testing your code…

Back to our example

```
def T1():
    amount −= 10000
    done1 = True

def T2():
    amount /= 2
    done2 = True

def main():
    await done1 and done2
    assert (amount == 40000) or (amount == 45000), amount

done1 = done2 = False
amount = 100000
spawn T1()
spawn T2()
spawn main()
```

Initialize shared variables

Back to our example

```
def T1():
    amount −= 10000
    done1 = True

def T2():
    amount /= 2
    done2 = True

def main():
    await done1 and done2
    assert (amount == 40000) or (amount == 45000), amount

done1 = done2 = False
amount = 100000
spawn T1()
spawn T2()
spawn main()
```

Spawn three processes (threads)

Back to our example

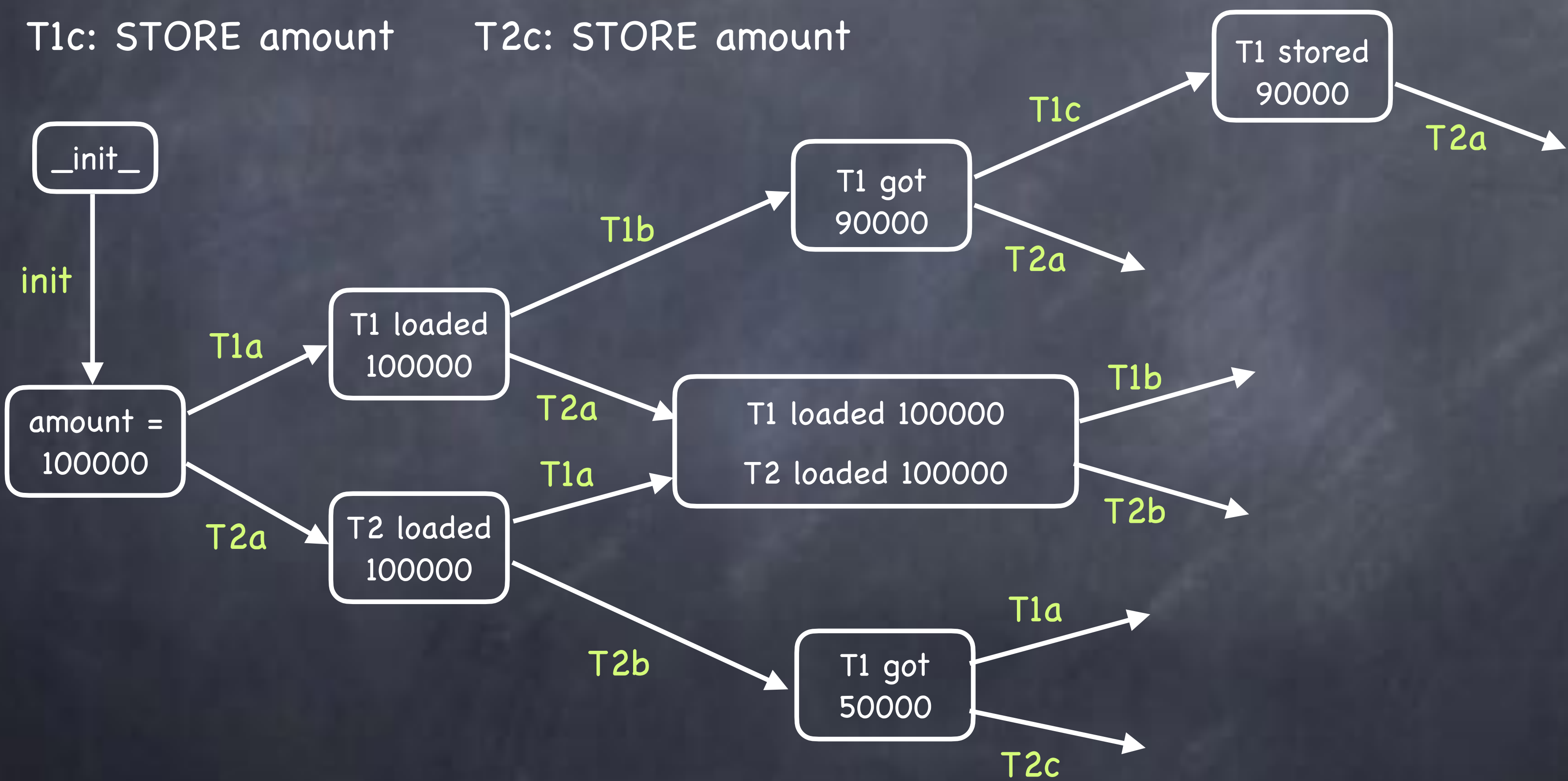
```
def T1():
    amount -= 10000
    done1 = True

def T2():
    amount /= 2
    done2 = True

def main():
    await done1 and done2
    assert (amount == 40000) or (amount == 45000), amount

done1 = done2 = False
amount = 100000
spawn T1()
spawn T2()
spawn main()
```

```
#states = 100 diameter = 5
==== Safety violation ====
__init__/() [0,40-58] 58 { amount: 100000, done1: False, done2: False }
T1/() [1-4]            5  { amount: 100000, done1: False, done2: False }
T2/() [10-17]         17  { amount: 50000,  done1: False, done2: True  }
T1/() [5-8]            8  { amount: 90000,  done1: True,  done2: True  }
main/() [19-23,25-34,36-37] 37 { amount: 90000, done1: True, done2: True }
>>> Harmony Assertion (file=test.hny, line=11) failed: 90000
```

Simplified model (ignoring main)

T1a: LOAD amount
T1b: SUB 10000
T1c: STORE amount

T2a: LOAD amount
T2b: DIV 2
T2c: STORE amount



Harmony Output

```
def T1():
    amount −= 10000
    done1 = True

def T2():
    amount /= 2
    done2 = True

def main():
    await done1 and done2
    assert (amount == 40000) or (amount == 45000), amount

done1 = done2 = False
amount = 100000
spawn T1()
spawn T2()
spawn main()
```

```
#states = 100 diameter = 5
==== Safety violation ====
__init__/() [0,40-58] 58 { amount: 100000, done1: False, done2: False }
T1/() [1-4]              5  { amount: 100000, done1: False, done2: False }
T2/() [10-17]           17 { amount: 50000,   done1: False, done2: True  }
T1/() [5-8]              8 { amount: 90000,   done1: True,  done2: True  }
main/() [19-23,25-34,36-37] 37 { amount: 90000, done1: True, done2: True }
>>> Harmony Assertion (file=test.hny, line=11) failed: 90000
```

Harmony Output

#states in the state graph

```
#states = 100 diameter = 5
==== Safety violation ====
__init__/() [0,40-58] 58 { amount: 100000, done1: False, done2: False }
T1/() [1-4]               5  { amount: 100000, done1: False, done2: False }
T2/() [10-17]            17 { amount: 50000,   done1: False, done2: True  }
T1/() [5-8]                8 { amount: 90000,   done1: True,  done2: True  }
main/() [19-23,25-34,36-37] 37 { amount: 90000, done1: True, done2: True }
>>> Harmony Assertion (file=test.hny, line=11) failed: 90000
```

Harmony Output

length of
the longest path
in turns

turns

```
#states = 100 diameter = 5
==== Safety violation ====
__init__/() [0,40-58] 58 { amount: 100000, done1: False, done2: False }
T1/() [1-4]               5  { amount: 100000, done1: False, done2: False }
T2/() [10-17]            17 { amount: 50000,   done1: False, done2: True  }
T1/() [5-8]               8 { amount: 90000,   done1: True,  done2: True  }
main/() [19-23,25-34,36-37] 37 { amount: 90000, done1: True, done2: True }
>>> Harmony Assertion (file=test.hny, line=11) failed: 90000
```

Harmony Output

Something went wrong in
(at least) one path in the graph
(assertion failure)

```
#states = 100 diameter = 5
==== Safety violation ====
__init__/() [0,40-58] 58 { amount: 100000, done1: False, done2: False }
T1/() [1-4]              5  { amount: 100000, done1: False, done2: False }
T2/() [10-17]           17 { amount: 50000,   done1: False, done2: True  }
T1/() [5-8]              8 { amount: 90000,   done1: True,  done2: True  }
main/() [19-23,25-34,36-37] 37 { amount: 90000, done1: True, done2: True }
>>> Harmony Assertion (file=test.hny, line=11) failed: 90000
```

Harmony Output

Shortest path to
assertion failure

```
#states = 100 diameter = 5
==== Safety violation ====
__init__/() [0,40-58] 58 { amount: 100000, done1: False, done2: False }
T1/() [1-4]             5  { amount: 100000, done1: False, done2: False }
T2/() [10-17]          17 { amount: 50000,   done1: False, done2: True  }
T1/() [5-8]             8 { amount: 90000,   done1: True,  done2: True  }
main/() [19-23,25-34,36-37] 37 { amount: 90000, done1: True, done2: True }
>>> Harmony Assertion (file=test.hny, line=11) failed: 90000
```

Harmony Output

T1a: LOAD amount
T1b: SUB 10000
T1c: STORE amount

T2a: LOAD amount
T2b: DIV 2
T2c: STORE amount

init

```
#states = 100 diameter = 5
==== Safety violation ====
__init__/() [0,40-58] 58 { amount: 100000, done1: False, done2: False }
T1/() [1-4]              5  { amount: 100000, done1: False, done2: False }
T2/() [10-17]           17 { amount: 50000,   done1: False, done2: True  }
T1/() [5-8]              8 { amount: 90000,   done1: True,  done2: True  }
main/() [19-23,25-34,36-37] 37 { amount: 90000, done1: True, done2: True }
>>> Harmony Assertion (file=test.hny, line=11) failed: 90000
```

Harmony Output

T1a: LOAD amount
T1b: SUB 10000
T1c: STORE amount

T2a: LOAD amount
T2b: DIV 2
T2c: STORE amount

T1ab

```
#states = 100 diameter = 5
==== Safety violation ====
__init__/() [0,40-58] 58 { amount: 100000, done1: False, done2: False }
T1/() [1-4]              5  { amount: 100000, done1: False, done2: False }
T2/() [10-17]           17  { amount: 50000,  done1: False, done2: True  }
T1/() [5-8]              8  { amount: 90000,  done1: True,  done2: True  }
main/() [19-23,25-34,36-37] 37 { amount: 90000, done1: True, done2: True }
>>> Harmony Assertion (file=test.hny, line=11) failed: 90000
```

Harmony Output

T1a: LOAD amount
T1b: SUB 10000
T1c: STORE amount

T2a: LOAD amount
T2b: DIV 2
T2c: STORE amount

T2abc

```
#states = 100 diameter = 5
==== Safety violation ====
__init__/() [0,40-58] 58 { amount: 100000, done1: False, done2: False }
T1/() [1-4]               5  { amount: 100000, done1: False, done2: False }
T2/() [10-17]            17 { amount: 50000,   done1: False, done2: True  }
T1/() [5-8]                8  { amount: 90000,   done1: True,  done2: True  }
main/() [19-23,25-34,36-37] 37 { amount: 90000, done1: True, done2: True }
>>> Harmony Assertion (file=test.hny, line=11) failed: 90000
```

Harmony Output

T1a: LOAD amount
T1b: SUB 10000
T1c: STORE amount

T2a: LOAD amount
T2b: DIV 2
T2c: STORE amount

```
#states = 100 diameter = 5
==== Safety violation ====
__init__/() [0,40-58] 58 { amount: 100000, done1: False, done2: False }
T1/() [1-4]               5  { amount: 100000, done1: False, done2: False }
T2/() [10-17]            17  { amount: 50000,   done1: False, done2: True  }
T1/() [5-8]               8  { amount: 90000,   done1: True,  done2: True  }
main/() [19-23,25-34,36-37] 37 { amount: 90000, done1: True, done2: True }
>>> Harmony Assertion (file=test.hny, line=11) failed: 90000
```

T1c

Harmony Output

T1a: LOAD amount
T1b: SUB 10000
T1c: STORE amount

T2a: LOAD amount
T2b: DIV 2
T2c: STORE amount

```
#states = 100 diameter = 5
==== Safety violation ====
__init__/() [0,40-58] 58 { amount: 100000, done1: False, done2: False }
T1/() [1-4]              5  { amount: 100000, done1: False, done2: False }
T2/() [10-17]           17 { amount: 50000,   done1: False, done2: True  }
T1/() [5-8]              8 { amount: 90000,   done1: True,  done2: True  }
main/() [19-23,25-34,36-37] 37 { amount: 90000, done1: True, done2: True }
>>> Harmony Assertion (file=test.hny, line=11) failed: 90000
```

main

Harmony Output

T1a: LOAD amount
T1b: SUB 10000
T1c: STORE amount

T2a: LOAD amount
T2b: DIV 2
T2c: STORE amount

```
#states = 100 diameter = 5
==== Safety violation ====
__init__/() [0,40-58] 58 { amount: 100000, done1: False, done2: False }
T1/() [1-4]              5  { amount: 100000, done1: False, done2: False }
T2/() [10-17]           17 { amount: 50000,   done1: False, done2: True  }
T1/() [5-8]              8 { amount: 90000,   done1: True,  done2: True  }
main/() [19-23,25-34,36-37] 37 { amount: 90000, done1: True, done2: True }
>>> Harmony Assertion (file=test.hny, line=11) failed: 90000
```

Harmony Output

```
#states = 100 diameter = 5
==== Safety violation ====
__init__/() [0,40-58] 58 { amount: 100000, done1: False, done2: False }
T1/() [1-4]            5  { amount: 100000, done1: False, done2: False }
T2/() [10-17]         17  { amount: 50000,  done1: False, done2: True  }
T1/() [5-8]            8  { amount: 90000,  done1: True,  done2: True  }
main/() [19-23,25-34,36-37] 37 { amount: 90000, done1: True, done2: True }
>>> Harmony Assertion (file=test.hny, line=11) failed: 90000
```

Harmony Output

Name of a thread

```
#states = 100 diameter = 5
==== Safety violation ====
__init__/() [0,40-58] 58 { amount: 100000, done1: False, done2: False }
T1/() [1-4]             5  { amount: 100000, done1: False, done2: False }
T2/() [10-17]          17  { amount: 50000,   done1: False, done2: True  }
T1/() [5-8]             8  { amount: 90000,   done1: True,  done2: True  }
main/() [19-23,25-34,36-37] 37 { amount: 90000, done1: True, done2: True }
>>> Harmony Assertion (file=test.hny, line=11) failed: 90000
```

Harmony Output

"steps" = list of program counters of machine instructions executed

```
#states = 100 diameter =
==== Safety violation ===
__init__/() [0,40-58] 58 { amount: 100000, done1: False, done2: False }
T1/() [1-4]            5  { amount: 100000, done1: False, done2: False }
T2/() [10-17]          17 { amount: 50000,   done1: False, done2: True  }
T1/() [5-8]            8  { amount: 90000,   done1: True,  done2: True  }
main/() [19-23,25-34,36-37] 37 { amount: 90000, done1: True, done2: True }
>>> Harmony Assertion (file=test.hny, line=11) failed: 90000
```

Harmony Machine code

```
0  Jump 40
1  Frame T1 ()
2  Load amount        T1a: LOAD amount
3  Push 10000
4  2-ary –            T1b: SUB 10000        def T1():
5  Store amount       T1c: STORE amount         amount –= 10000
6  Push True                                    done1 = True
7  Store done1        T1d: done1 = True
8  Return
9  Jump 40
10 Frame T2 ()
11 Load amount        T2a: LOAD amount
12 Push 2
13 2-ary /            T2b: DIV 2            def T2():
14 Store amount       T1c: STORE amount         amount /= 2
15 Push True                                    done2 = True
16 Store done2        T1d: done2 = True
17 Return
18 …
```

Harmony Machine code

```
0  Jump 40               PC := 40
1  Frame T1 ()
2  Load amount           push amount onto the stack of Thread T1
3  Push 10000            push 10000 onto the stack of Thread T1
4  2-ary –               replace top two elements of stack with difference
5  Store amount          store  top of stack of T1 into amount
6  Push True             push True onto stack of T1
7  Store done1           store  top of stack of T1 into done1
8  Return
9  Jump 40
10 Frame T2 ()
11 Load amount           push amount onto the stack of Thread T2
12 Push 2                push 2 onto the stack of Thread T2
13 2-ary /               replace top two elements of stack with quotient
14 Store amount          store  top of stack of T1 into amount
15 Push True             push True onto stack of T2
16 Store done2           store  top of stack of T1 into done2
17 Return
18 …
```

Harmony Output

current program counter
(after turn)

```
#states = 100 diameter = 5
==== Safety violation ====
__init__/() [0,40-58] 58 { amount: 100000, done1: False, done2: False }
T1/() [1-4]            5 { amount: 100000, done1: False, done2: False }
T2/() [10-17]         17 { amount: 50000,  done1: False, done2: True  }
T1/() [5-8]            8 { amount: 90000,  done1: True,  done2: True  }
main/() [19-23,25-34,36-37] 37 { amount: 90000, done1: True, done2: True }
>>> Harmony Assertion (file=test.hny, line=11) failed: 90000
```

Harmony Output

current state (after turn)

```
#states = 100 diameter = 5
==== Safety violation ====
__init__/() [0,40-58] 58 { amount: 100000, done1: False, done2: False }
T1/() [1-4]            5  { amount: 100000, done1: False, done2: False }
T2/() [10-17]         17  { amount: 50000,   done1: False, done2: True  }
T1/() [5-8]            8  { amount: 90000,   done1: True,  done2: True  }
main/() [19-23,25-34,36-37] 37 { amount: 90000, done1: True, done2: True }
>>> Harmony Assertion (file=test.hny, line=11) failed: 90000
```

Harmony's VM State

- Three parts:
  - code (which never changes)
  - values of shared variables
  - states of each of the running processes
    - a.k.a. "contexts"

State represents one vertex in the graph model

Context (State of a Process)

- Method name and parameters
- PC (program counter)
- stack (+ implicit stack pointer)
- local variables
  - parameters (a.k.a. arguments)
  - result
    - there is no return statement
  - local variables
    - declared in var, let, and for statements

Harmony != Python

Harmony	Python
tries all possible executions	executes just one
(…) == […] == …	1 != [1] != (1)
1, == [1,] == (1,) != (1) == [1] == 1	[1,] == [1] != (1) == 1 != (1,)
f(1) == f 1 == f[1]	f 1 and f[1] are illegal (if f is method)
{ } is empty set	{ } is empty dictionary
few operator precedence rules --- use parentheses often	many operator precedence rules
variables global unless declared otherwise	depends... Sometimes must be explicitly declared global
no **return**, **break**, **continue**	various flow control escapes
no classes	object-oriented
…	…

I/O in Harmony

- Input
  - choose expression
    - $x =$ choose$(\{1{,}2{,}3\})$
    - allows Harmony to know all possible inputs
  - const expression
    - const $x = 3$
    - can be overridden with "$-c\ x = 4$" to Harmony
- Output
  - print $x + y$
  - assert $x + y < 10, (x, y)$

I/O in Harmony

- Input

No open(), read(), or input() statements

y

- Output
  - print $x + y$
  - assert $x + y < 10, (x, y)$

Non-determinism in Harmony

- Three sources
  - choose expressions
  - thread interleavings
  - interrupts

Limitation: Models must be finite!

- But models are allowed to have cycles
- Executions are allowed to be unbounded
- Harmony checks for the possibility of termination

Back to our problem...

Two threads updating shared variable amount

- T_1 wants to decrement amount by \$10K
- T_2 wants to decrement amount by 50%

T_1

```
. . .
amount := amount - 10,000;
. . .
```

T_2

```
. . .
amount := amount * 0.5;
. . .
```

Memory   amount 100,000

How to "serialize" these executions?

Critical Section

Shared memory access: must be serialized

T_1

```
. . .
CSEnter()
    amount := amount - 10,000;
CSExit()
. . .
```

T_2

```
. . .
CSEnter()
    amount := amount * 0.5;
CSExit()
. . .
```

- Goals
  - Mutual exclusion: at most 1 thread in CS at any time
  - Progress: all threads wanting to enter CS eventually do
  - Fairness: equal chances to get into CS (uncommon in practice)

Critical Section

Shared memory access: must be serialized

T_1

```
. . .
CSEnter()
   amount := amount - 10,000;
CSExit()
. . .
```

T_2

```
. . .
CSEnter()
     amount := amount * 0.5;
CSExit()
. . .
```

- Goals
  - Mutual exclusion: at most 1 thread in CS at any time
  - Progress: if any threads want to enter the CS, at least one does

What makes the Critical Section problem hard?

- Mutual exclusion?
- Progress?
- It is the combination!
  - both properties, on their own, are trivial to achieve
  - there is much more to this...

Critical Sections in Harmony

```
def thread(self):
    while True
      … # code outside critical section
      … # code to enter the critical section
      … # critical section itself
      … # code to exit the critical section


spawn T1()
spawn T2()
…
```

How do we check mutual exclusion?

How do we check progress?

Critical Sections in Harmony

```
def thread(self):
    while True
      … # code outside critical section
      … # code to enter the critical section
      … # critical section itself
      … # code to exit the critical section


spawn T1()
spawn T2()
…
```

How do we check mutual exclusion?

Critical Sections in Harmony

```
def thread(self):
    while True
      … # code outside critical section
      … # code to enter the critical section
      cs:  assert countLabel(cs) ==1
      … # code to exit the critical section


spawn T1()
spawn T2()
…
```

How do we check mutual exclusion?

Critical Sections in Harmony

```
def thread(self):
    while True
      … # code outside critical section
      … # code to enter the critical section
      cs:  assert countLabel(cs) ==1
      … # code to exit the critical section


spawn T1()
spawn T2()
…
```

How do we check progress?

Critical Sections in Harmony

```
def thread(self):
    while choose({False, True}):
      … # code outside critical section
      … # code to enter the critical section
      cs:  assert countLabel(cs) ==1
      … # code to exit the critical section


spawn T1()
spawn T2()
…
```

How do we check progress?

If code to enter/exit the critical section cannot terminate, Harmony will complain!

All you need is locks (tatta-rararaaa...)

- At most one thread can hold the lock
- Acquire the lock to enter the CS
- Release the lock when exiting
- But how does one build a lock?

Try 1: A Naïve Lock

```
lockTaken = False

def thread(self):
    while choose({ False, True }):
        # Enter critical section
        await not lockTaken
        lockTaken = True

        # Critical section
        cs: assert countLabel(cs) == 1

        # Leave critical section
        lockTaken = False

spawn thread(0)
spawn thread(1)
```

Try 1: A Naïve Lock

```
lockTaken = False

def thread(self):
    while choose({ False, True }):
        # Enter critical section
        await not lockTaken
        lockTaken = True

        # Critical section
        cs: assert countLabel(cs) == 1

        # Leave critical section
        lockTaken = False

spawn thread(0)
spawn thread(1)
```

Wait till lock is free, then take it

Release the lock

Try 1: A Naïve Lock

```
lockTaken = False

def thread(self):
    while choose({ False, True }):
        # Enter critical section
        await not lockTaken
        lockTaken = True

        # Critical section
        cs: assert countLabel(cs) == 1

        # Leave critical section
        lockTaken = False

spawn thr
spawn thr
```

Testing and setting the lock is not atomic!

Wait till lock is free, then take it

Release the lock

==== Safety violation ====

__init__/() [0,26-36]	36 { lockTaken: False }
thread/0 [1-2,3(choose True),4-7]	8 { lockTaken: False }
thread/1 [1-2,3(choose True),4-8]	9 { lockTaken: True }
thread/0 [8-19]	19 { lockTaken: True }

>>> Harmony Assertion (file=code/naiveLock.hny, line=10) failed

Try 2: Flags

```
flags = [ False, False ]

def thread(self):
    while choose({ False, True }):
        # Enter critical section
        flags[self] = True
        await not flags[1 − self]

        # Critical section
        cs: assert countLabel(cs) == 1

        # Leave critical section
        flags[self] = False

spawn thr
spawn thr
```

Invariant:
Thread i in CS
⟹
flag[i] = True

Signal you want to enter

If someone in the CS, wait

Signal out of CS

==== Non-terminating State ===
__init__/() [0,36-46] 46 { flags: [False, False] }
thread/0 [1-2,3(choose True),4-12] 13 { flags: [True, False] }
thread/1 [1-2,3(choose True),4-12] 13 { flags: [True, True] }
blocked thread: thread/1 pc = 13
blocked thread: thread/0 pc = 13

Try 3: Turns

```
turn = 0

def thread(self):
    while choose({ False, True }):
        # Enter critical section
        turn = 1 − self
        await turn == self

        # Critical section
        cs: a

        # Le

spawn thr
spawn thread(1)
```

Invariant:
Thread i in CS
⟹
turn = i

After you...

Wait for your turn

==== Non-terminating State ===
__init__/() [0,28-38] 38 { turn: 0 }
thread/0 [1-2,3(choose True),4-26,2,3(choose True),4] 5 { turn: 1 }
thread/1 [1-2,3(choose False),4,27] 27 { turn: 1 }
blocked thread: thread/0 pc = 5

Peterson's Algorithm: Flags and Turns!

```
sequential flags, turn
```

Prevents out-of-order execution

```
flags = [ False, False ]
turn = choose({0, 1})

def thread(self):
    while choose({ False, True }):
        # Enter critical section
        flags[self] = True
```

I'd like to enter...

```
        turn = 1 − self
```

...but you go first!

```
        await (not flags[1 − self]) or (turn == self)
```

Wait until alone or it's my turn

```
        # Critical section is here
        cs: assert countLabel(cs) == 1

        # Leave critical section
        flags[self] = False
```

Leave

```
spawn thread(0)
spawn thread(1)
```

#states = 104 diameter = 5
#components: 37
no issues found

What about a proof?

- To understand why it works...
- We need to show that, for any execution, all states reached satisfy mutual exclusion
  - i.e., that mutual exclusion is an invariant
- See the Harmony book for a proof!

Harmony Interlude: Pointers

- If x is a shared variable, $?x$ is the address of x
- If p is a shared variable, and $p == ?x$, then we say that p is a pointer to x
- Finally, $!p$ refers to the value of x

Using a lock for a critical section

```
import synch

const NTHREADS = 2

lock = synch.Lock()

def thread():
    while choose({ False, True }):
        synch.acquire(?lock)
        cs: assert countLabel(cs) == 1
        synch.release(?lock)

for i in {1..NTHREADS}:
    spawn thread()
```