CHESS: Analysis and Testing of Concurrent Programs

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Concurrent Programming is HARD

- Concurrent executions are highly nondeterminisitic
- Rare thread interleavings result in Heisenbugs
  - Difficult to find, reproduce, and debug
- Observing the bug can “fix” it
  - Likelihood of interleavings changes, say, when you add printfs
- A huge productivity problem
  - Developers and testers can spend weeks chasing a single Heisenbug

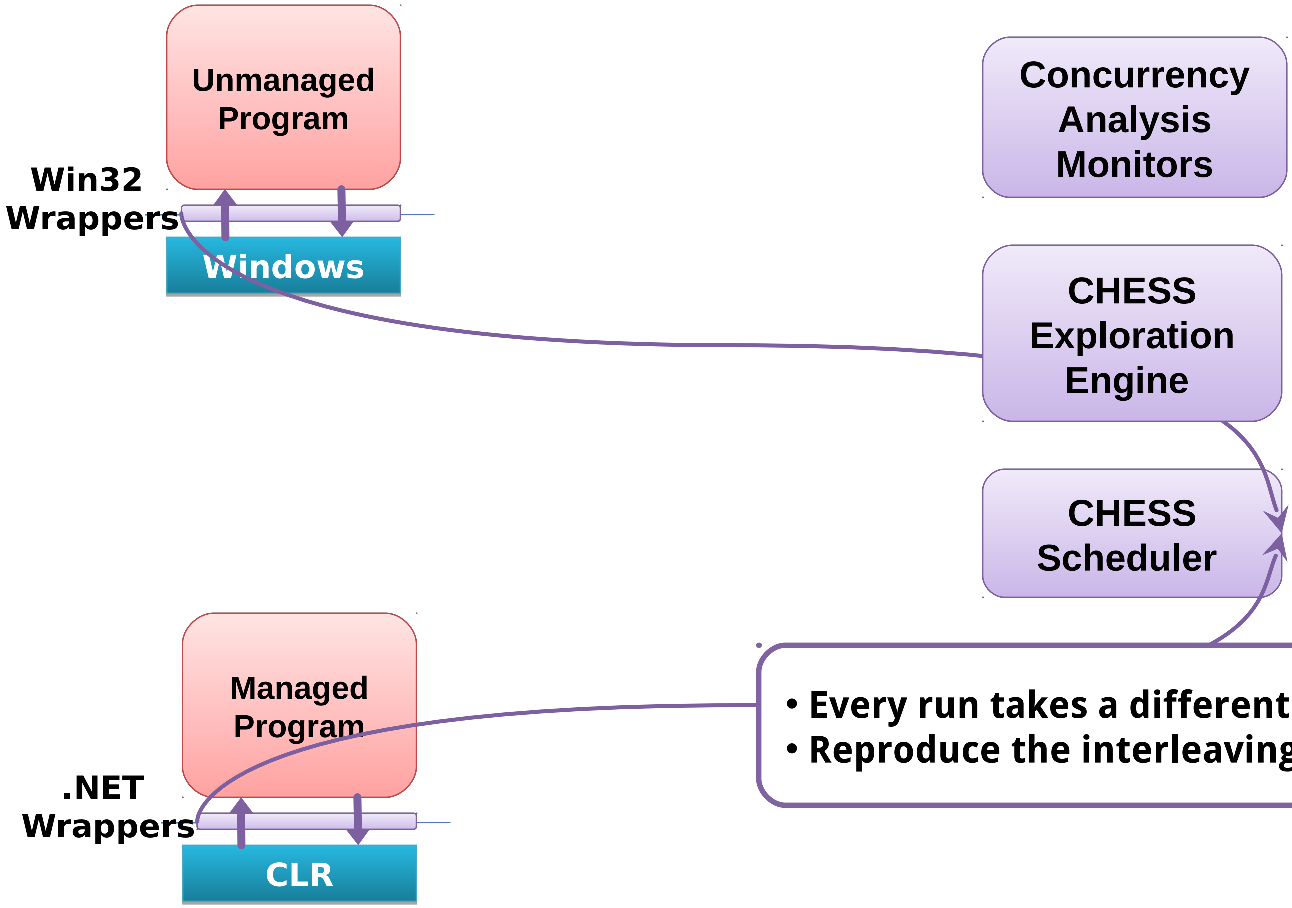
Main Takeaways

- You can find and reproduce Heisenbugs
  - new automatic tool called CHESS
  - for Win32 and .NET
- CHESS used extensively inside Microsoft
  - Parallel Computing Platform (PCP)
  - Singularity
  - Dryad/Cosmos
- Released by DevLabs

CHESS in a nutshell

- CHESS is a user-mode scheduler
  - Controls all scheduling nondeterminism
- Guarantees:
  - Every program run takes a different thread interleaving
  - Reproduce the interleaving for every run
- Provides monitors for analyzing each execution

CHESS Architecture

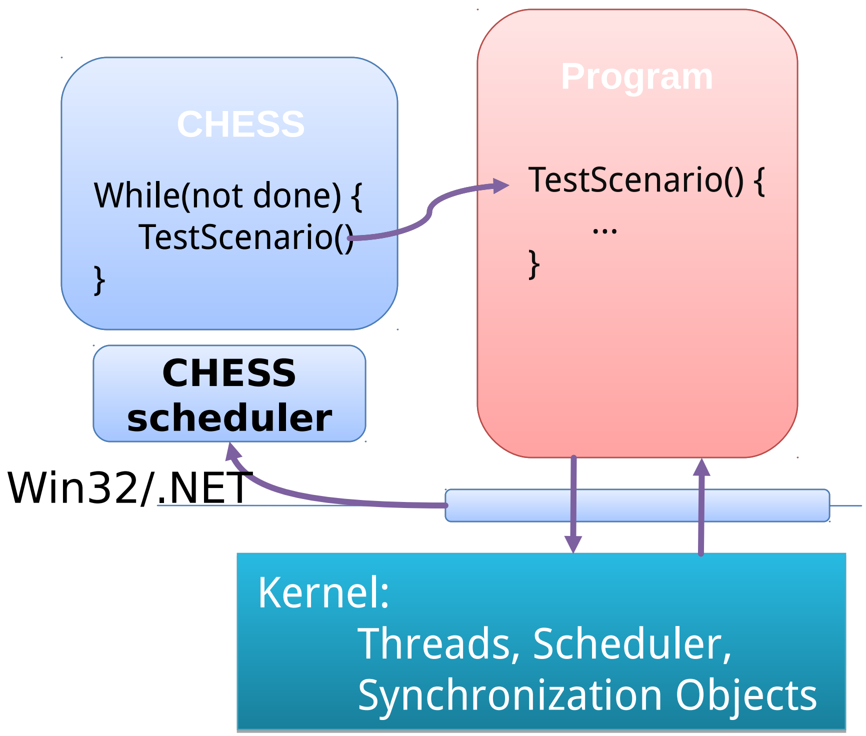


- Every run takes a different interleaving
- Reproduce the interleaving for every run

CHESS Specifics

- Ability to explore all interleavings
  - Need to understand complex concurrency APIs (Win32, System.Threading)
  - Threads, threadpools, locks, semaphores, async I/O, APCs, timers, …
- Does not introduce false behaviors
  - Any interleaving produced by CHESS is possible on the real scheduler

CHESS: Find and Reproduce Heisenbugs



CHESS runs the scenario in a loop

- Every run takes a different interleaving
- Every run is repeatable

Uses the CHESS scheduler

- To control and direct interleavings

Detect

- Assertion violations
- Deadlocks
- Dataraces
- Livelocks

The Design Space for CHESS

- Scale
  - Apply to large programs
- Precision
  - Any error found by CHESS is possible in the wild
  - CHESS should not introduce any new behaviors
- Coverage
  - Any error found in the wild can be found by CHESS
  - Capture all sources of nondeterminism
  - Exhaustively explore the nondeterminism

CHESS Scheduler

Concurrent Executions are Nondeterministic

Thread 1

```
x = 1;
y = 1;
```

Thread 2

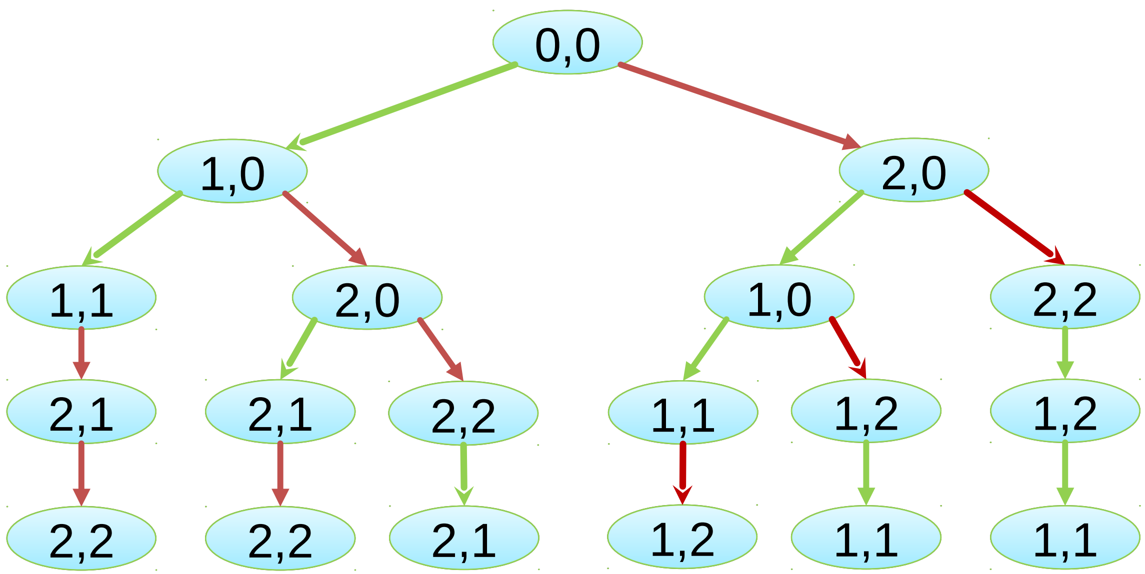
```
x = 2;
y = 2;
```

```
x = 1;
```

```
y = 1;
```

```
x = 2;
```

```
y = 2;
```



High level goals of the scheduler

- Enable CHESS on real-world applications
  - IE, Firefox, Office, Apache, ...
- Capture all sources of nondeterminism
  - Required for reliably reproducing errors
- Ability to explore these nondeterministic choices
  - Required for finding errors

Sources of Nondeterminism
1. Scheduling Nondeterminism

- Interleaving nondeterminism
  - Threads can race to access shared variables or monitors
  - OS can preempt threads at arbitrary points
- Timing nondeterminism
  - Timers can fire in different orders
  - Sleeping threads wake up at an arbitrary time in the future
  - Asynchronous calls to the file system complete at an arbitrary time in the future

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  - Timers can fire in different orders
  - Sleeping threads wake up at an arbitrary time in the future
  - Asynchronous calls to the file system complete at an arbitrary time in the future
- CHESS captures and explores this nondeterminism

Sources of Nondeterminism
2. Input nondeterminism

- User Inputs
  - User can provide different inputs
  - The program can receive network packets with different contents

- Nondeterministic system calls
  - Calls to gettimeofday(), random()
  - ReadFile can either finish synchronously or asynchronously

Sources of Nondeterminism
2. Input nondeterminism

- User Inputs
  - User can provide different inputs
  - The program can receive network packets with different contents
  - CHESS relies on the user to provide a scenario
- Nondeterministic system calls
  - Calls to gettimeofday(), random()
  - ReadFile can either finish synchronously or asynchronously
  - CHESS provides wrappers for such system calls

Sources of Nondeterminism
3. Memory Model Effects

- Hardware relaxations
  - The processor can reorder memory instructions
  - Can potentially introduce new behavior in a concurrent program

- Compiler relaxations
  - Compiler can reorder memory instructions
  - Can potentially introduce new behavior in a concurrent program (with data races)

Sources of Nondeterminism
3. Memory Model Effects

- Hardware relaxations
  - The processor can reorder memory instructions
  - Can potentially introduce new behavior in a concurrent program
  - CHESS contains a monitor for detecting such relaxations
- Compiler relaxations
  - Compiler can reorder memory instructions
  - Can potentially introduce new behavior in a concurrent program (with data races)
  - Future Work

Interleaving Nondeterminism: Example

```
init:
  balance = 100;
```

Deposit Thread

```
void Deposit100(){
  EnterCriticalSection(&cs);
  balance += 100;
  LeaveCriticalSection(&cs);
}
```

Withdraw Thread

```
void Withdraw100(){
  int t;

  EnterCriticalSection(&cs);
  t = balance;
  LeaveCriticalSection(&cs);

  EnterCriticalSection(&cs);
  balance = t - 100;
  LeaveCriticalSection(&cs);

}
```

```
final:
  assert(balance = 100);
```

Invoke the Scheduler at Preemption Points

Deposit Thread

```
void Deposit100(){
  ChessSchedule();
  EnterCriticalSection(&cs);
  balance += 100;
  ChessSchedule();
  LeaveCriticalSection(&cs);
}
```

Withdraw Thread

```
void Withdraw100(){
  int t;

  ChessSchedule();
  EnterCriticalSection(&cs);
  t = balance;
  ChessSchedule();
  LeaveCriticalSection(&cs);

  ChessSchedule();
  EnterCriticalSection(&cs);
  balance = t - 100;
  ChessSchedule();
  LeaveCriticalSection(&cs);

}
```

Introducing Unpredictable Delays

Deposit Thread

```
void Deposit100(){
  Sleep( rand () );
  EnterCriticalSection(&cs);
  balance += 100;
  Sleep( rand() );
  LeaveCriticalSection(&cs);
}
```

Withdraw Thread

```
void Withdraw100(){
  int t;

  Sleep( rand() );
  EnterCriticalSection(&cs);
  t = balance;
  Sleep( rand() );
  LeaveCriticalSection(&cs);

  Sleep( rand() );
  EnterCriticalSection(&cs);
  balance = t - 100;
  Sleep( rand() );
  LeaveCriticalSection(&cs);

}
```

Introduce Predictable Delays with Additional Synchronization

Deposit Thread

```
void Deposit100(){




      WaitEvent( e1 );
   EnterCriticalSection(&cs);
   balance += 100;
   LeaveCriticalSection(&cs);
      SetEvent( e2 );
}
```

Withdraw Thread

```
void Withdraw100(){
   int t;

   EnterCriticalSection(&cs);
   t = balance;
   LeaveCriticalSection(&cs);
      SetEvent( e1 );




      WaitEvent( e2 );
   EnterCriticalSection(&cs);
   balance = t - 100;
   LeaveCriticalSection(&cs);
}
```

Blindly Inserting Synchronization Can Cause Deadlocks

Deposit Thread

```
void Deposit100(){
  EnterCriticalSection(&cs);
  balance += 100;




    WaitEvent( e1 );
  LeaveCriticalSection(&cs);

}
```

Withdraw Thread

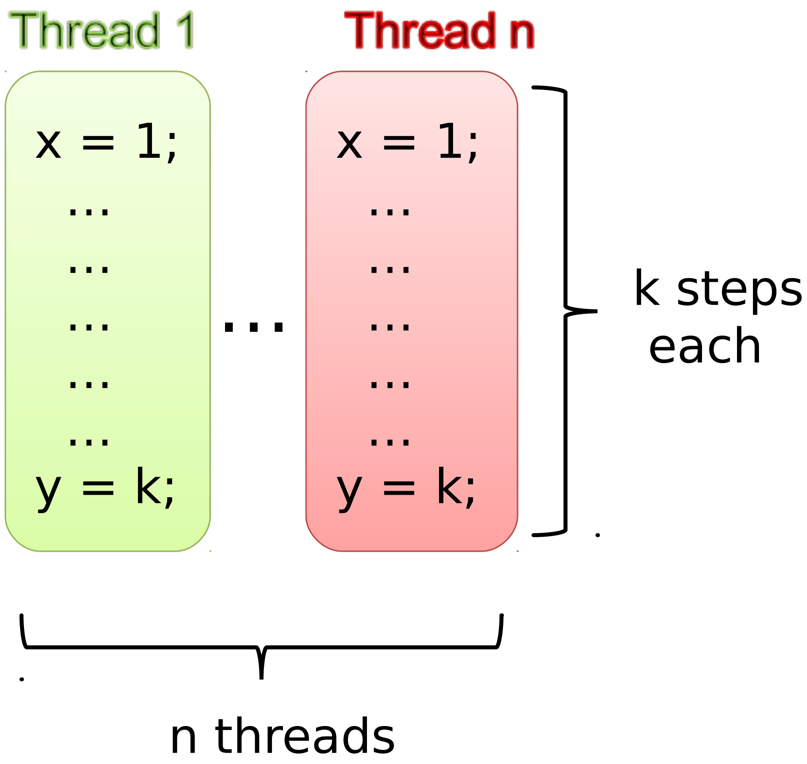
```
void Withdraw100(){
  int t;

  EnterCriticalSection(&cs);
  t = balance;
  LeaveCriticalSection(&cs);
    SetEvent( e1 );








  EnterCriticalSection(&cs);
  balance = t - 100;
  LeaveCriticalSection(&cs);
}
```

CHESS Scheduler Basics

- Introduce an event per thread
- Every thread blocks on its event
- The scheduler wakes one thread at a time by enabling the corresponding event
- The scheduler does not wake up a *disabled* thread
  - Need to know when a thread can make progress
  - Wrappers for synchronization provide this information
- The scheduler has to pick one of the enabled threads
  - The exploration engine decides for the scheduler

CHESS Algorithms

State space explosion

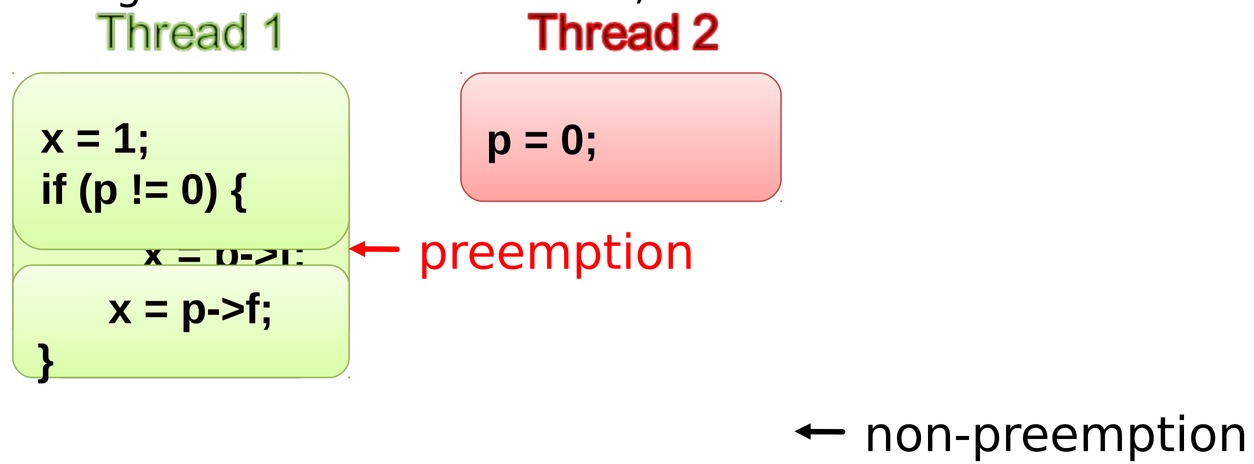


- Number of executions $= O(n^{nk})$
- Exponential in both n and k
  - Typically: $n < 10$ $k > 100$
- Limits scalability to large programs

Goal: Scale CHESS to large programs (large k)

Preemption bounding

- CHESS, by default, is a non-preemptive, starvation-free scheduler
  - Execute huge chunks of code atomically
- Systematically insert a small number preemptions
  - Preemptions are context switches forced by the scheduler
    - e.g. Time-slice expiration
  - Non-preemptions – a thread voluntarily yields
    - e.g. Blocking on an unavailable lock, thread end

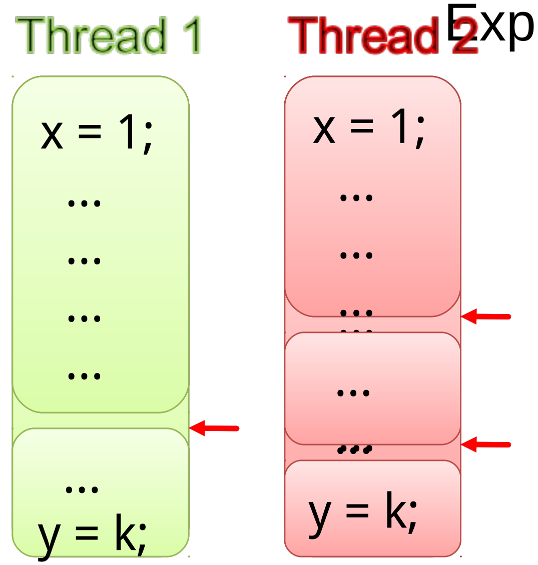


Polynomial state space

- Terminating program with fixed inputs and deterministic threads
  - n threads, k steps each, c preemptions
- Number of executions <= ${}_{nk}C_c$. $(n+c)!$

  $= O((n^2k)^c . n!)$

Exponential in n and c, but not in k



- Choose c preemption points
- Permute n+c atomic blocks

Advantages of preemption bounding

- Most errors are caused by few (<2) preemptions
- Generates an easy to understand error trace
  - Preemption points almost always point to the root-cause of the bug
- Leads to good heuristics
  - Insert more preemptions in code that needs to be tested
  - Avoid preemptions in libraries
  - Insert preemptions in recently modified code
- A good coverage guarantee to the user
  - When CHESS finishes exploration with 2 preemptions, any remaining bug requires 3 preemptions or more

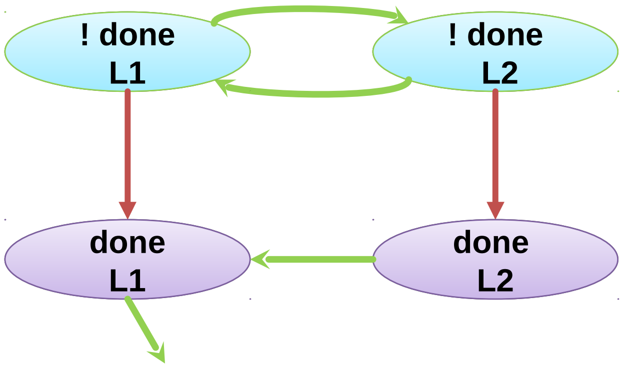
Concurrent programs have cyclic state spaces

Thread 1

```
L1:  while( ! done) {
L2:      Sleep();
      }
```

Thread 2

```
M1: done = 1;
```



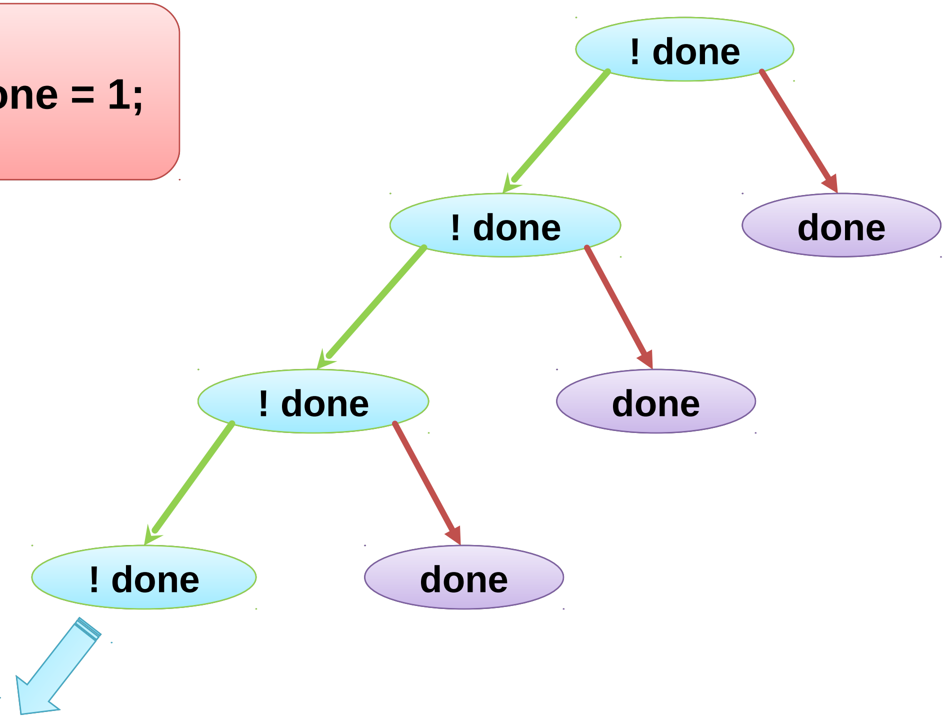
A demonic scheduler unrolls any cycle ad-infinitum

Thread 1

```
while( ! done)
{
    Sleep();
}
```

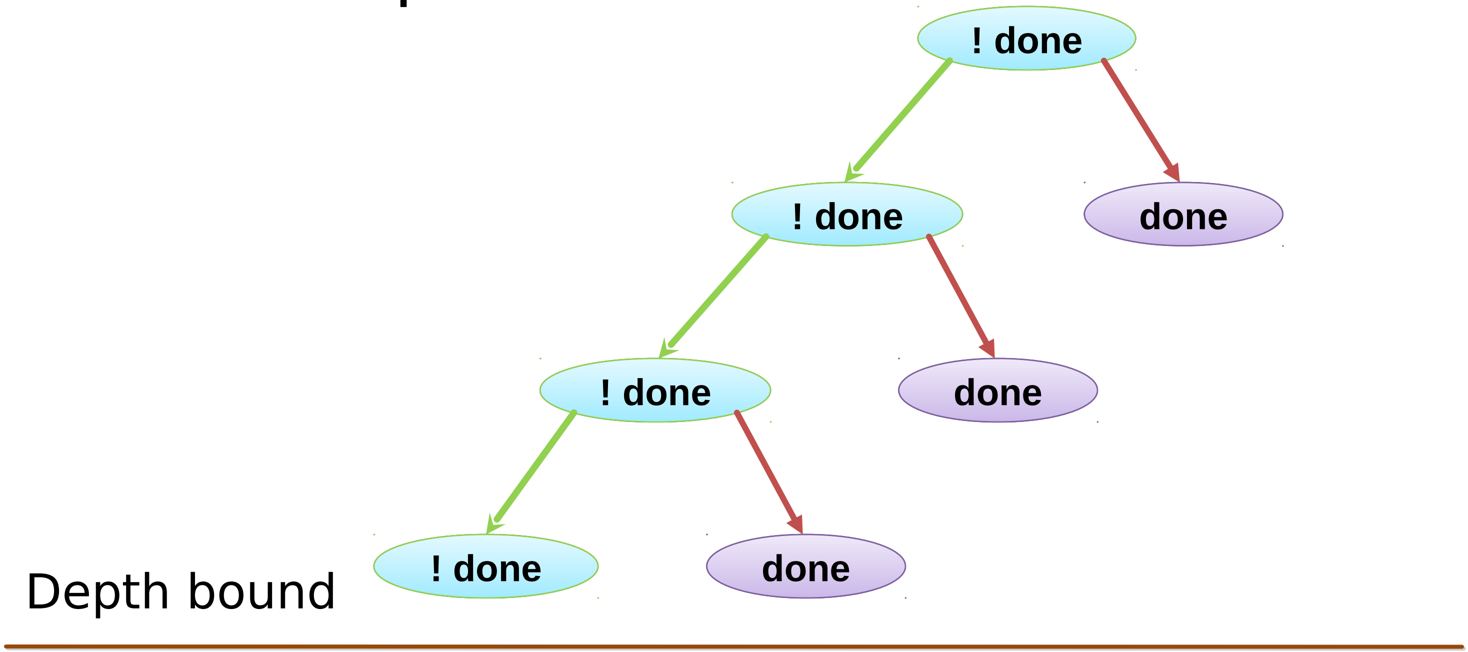
Thread 2

```
done = 1;
```



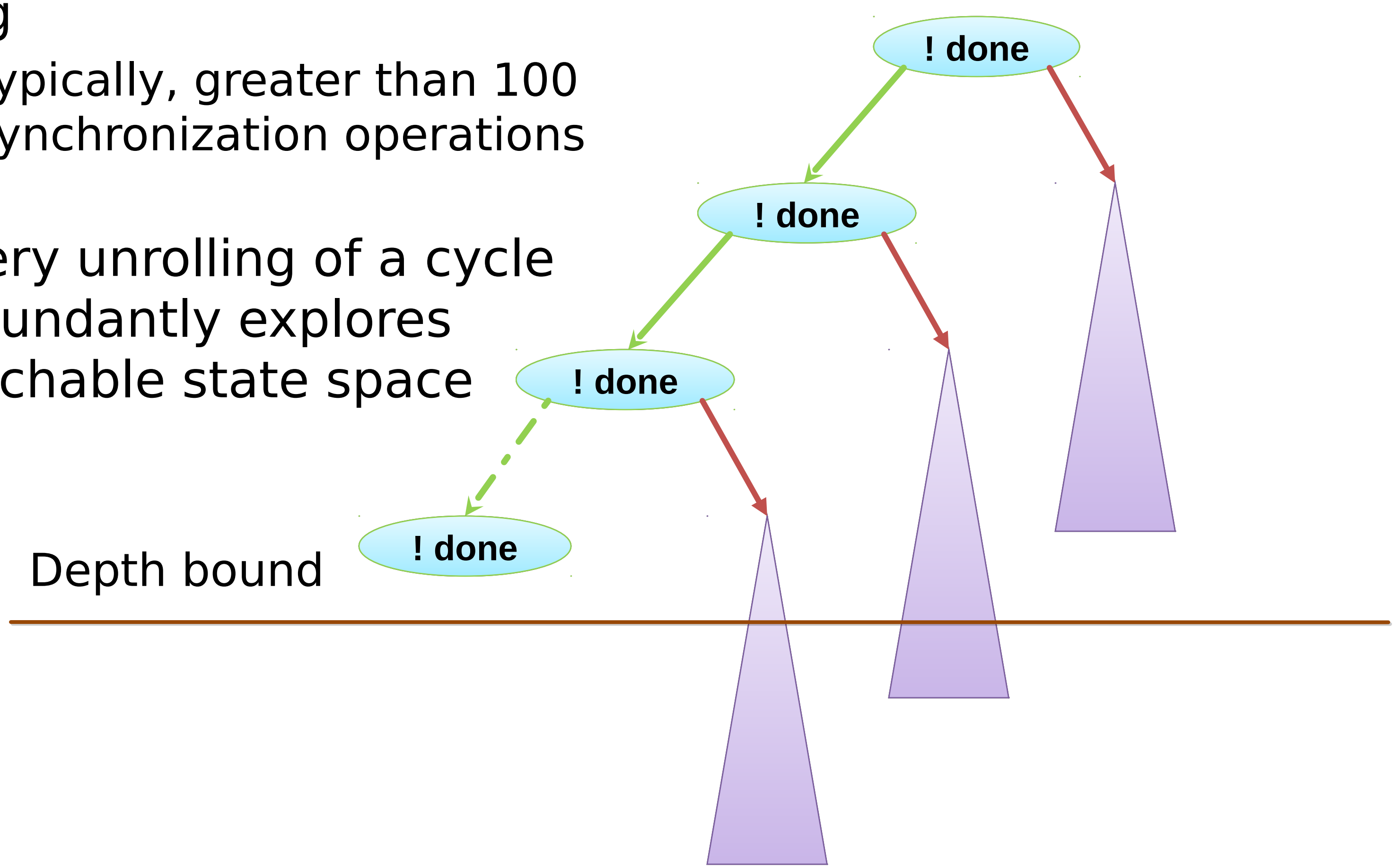
Depth bounding

- Prune executions beyond a bounded number of steps



Problem 1: Ineffective state coverage

- Bound has to be large enough to reach the deepest bug
  - Typically, greater than 100 synchronization operations
- Every unrolling of a cycle redundantly explores reachable state space



Problem 2: Cannot find livelocks

- Livelocks : lack of progress in a program

Thread 1

```
temp = done;
while( ! temp)
{
    Sleep();
}
```

Thread 2

```
done = 1;
```

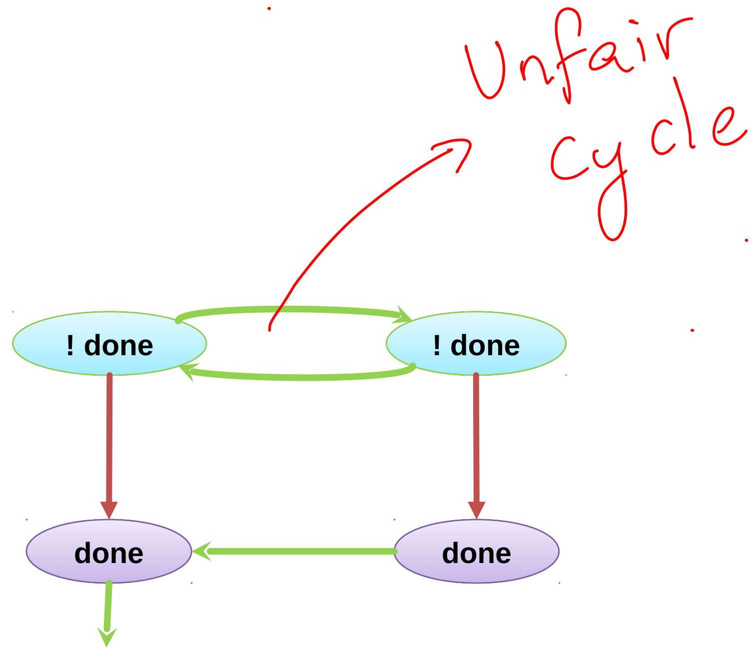
Key idea

Thread 1

```
while( ! done)
{
    Sleep();
}
```

Thread 2

```
done = 1;
```

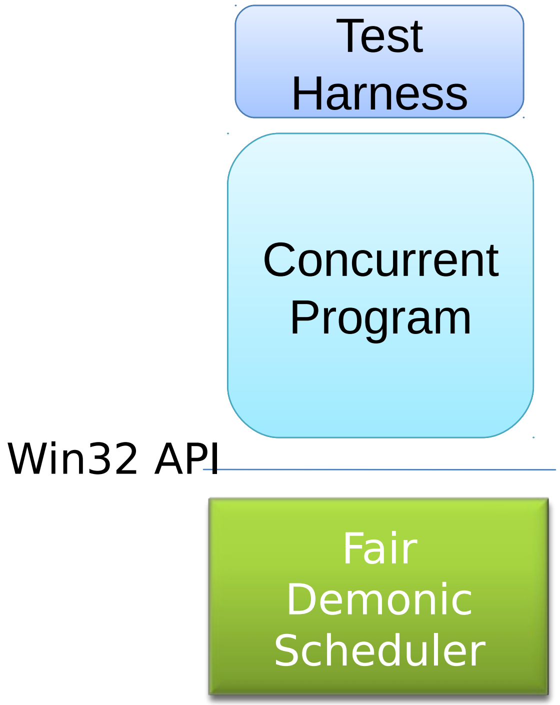


- This test terminates only when the scheduler is fair
- Fairness is assumed by programmers

All cycles in correct programs are unfair

A fair cycle is a livelock

We need a fair scheduler



- Avoid unrolling unfair cycles
  - Effective state coverage
- Detect fair cycles
  - Find livelocks

- What notion of “fairness” do we use?

Weak fairness

- A thread that remains enabled should eventually be scheduled

Thread 1

```
while( ! done)
{
     Sleep();
}
```

Thread 2

```
done = 1;
```

- A weakly-fair scheduler will eventually schedule Thread 2
- Example: round-robin

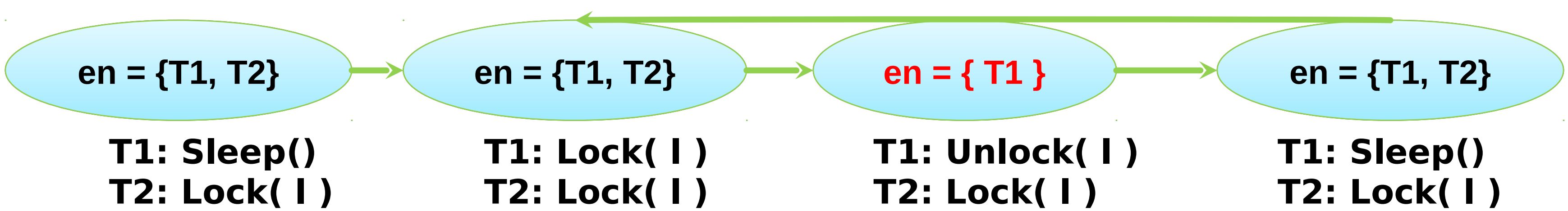
Weak fairness does not suffice

Thread 1

```
Lock( l );
While( ! done)
{
    Unlock( l );
    Sleep();
    Lock( l );
}
Unlock( l );
```

Thread 2

```
Lock( l );
done = 1;
Unlock( l );
```



Strong Fairness

- A thread that is enabled infinitely often is scheduled infinitely often

Thread 1

```
Lock( l );
While( ! done)
{
    Unlock( l );
    Sleep();
    Lock( l );
}
Unlock( l );
```

Thread 2

```
Lock( l );
done = 1;
Unlock( l );
```

- Thread 2 is enabled and competes for the lock infinitely often

Implementing a strongly-fair scheduler

- A round-robin scheduler with priorities

- Operating system schedulers
  - Priority boosting of threads

We also need to be demonic

- Cannot generate all fair schedules
  - There are infinitely many, even for simple programs
- It is sufficient to generate enough fair schedules to
  - Explore all states (safety coverage)
  - Explore at least one fair cycle, if any (livelock coverage)

(Good) Programs indicate lack of progress

Thread 1

```
while( ! done)
{
    Sleep();
}
```

Thread 2

```
done = 1;
```

- Good Samaritan assumption:
  - A thread when scheduled infinitely often yields the processor infinitely often
- Examples of yield:
  - Sleep()
  - Blocking on synchronization operation
  - Thread completion

Fair demonic scheduler

- Maintain a priority-order (a partial-order) on threads
  - t < u : t will not be scheduled when u is enabled
- Threads get a lower priority only when they yield
  - When t yields, add t < u if
    - Thread u was continuously enabled since last yield of t, or
    - Thread u was disabled by t since the last yield of t
- A thread loses its priority once it executes
  - Remove all edges t < u when u executes

Data Races

What is a Data Race?

- If two *conflicting* memory accesses happen *concurrently,* we have a data race.
- Two memory accesses *conflict* if
  - They target the same location
  - They are not both reads
  - They are not both synchronization operations
- Best practice: write “correctly synchronized“ programs that do not contain data races.

What Makes Data Races significant?

- Data races may reveal synchronization errors
  - Most typically, programmer forgot to take a lock, or declare a variable volatile.
- Race-free programs are easier to verify
  - If a program is race-free, it is enough to consider schedules that preempt on synchronizations only
  - CHESS heavily relies on this reduction

How do we find races?

- Remember: races are concurrent conflicting accesses.
- But what does concurrent actually mean?
- Two general approaches to do race-detection

Lockset-Based (heuristic) Concurrent ≈ *"Disjoint locksets"*	Happens-Before-Based (precise) Concurrent = *"Not ordered by happens-before"*

Synchronization = Locks ???

- This C# code contains neither locks nor a data race:

```
int data;
volatile bool flag;
```

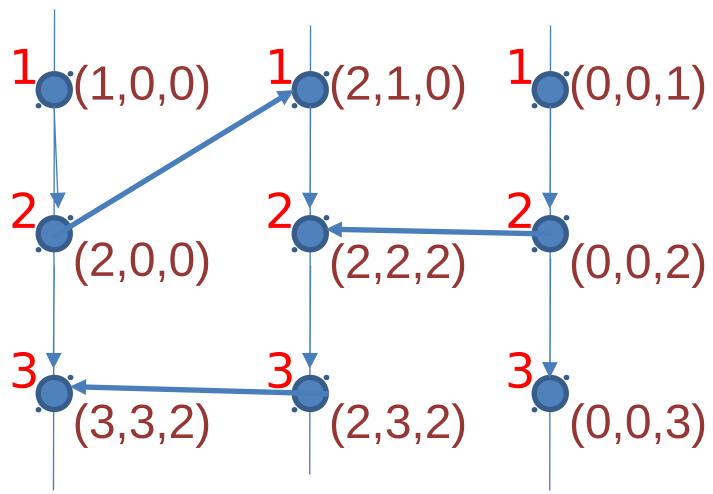
Thread 1	Thread 2

`data = 1;`
`flag = true;`
	`while (!flag)`
	`    yield();`
	`int x = data;`

- CHESS is *precise*: does not report this as a race. But *does* report a race if you remove the ‘volatile’ qualifier.

Happens-Before Order [Lamport]

- Use logical clocks and timestamps to define a partial order called *happens-before* on events in a concurrent system
- States *precisely* when two events are *logically* concurrent (abstracting away real time)



- Cross-edges from send events to receive events
- (a_1, a_2, a_3) happens before (b_1, b_2, b_3) iff $a_1 \leq b_1$ and $a_2 \leq b_2$ and $a_3 \leq b_3$

Happens-Before for Shared Memory

- Distributed Systems:
  Cross-edges from send to receive events

- Shared Memory systems:
  Cross-edges represent ordering effect of synchronization
  - Edges from lock release to subsequent lock acquire
  - Edges from volatile writes to subsequent volatile reads
  - Long list of primitives that may create edges
    - Semaphores
    - Waithandles
    - Rendezvous

Example

Static Program

```
int data;
volatile bool flag;
```

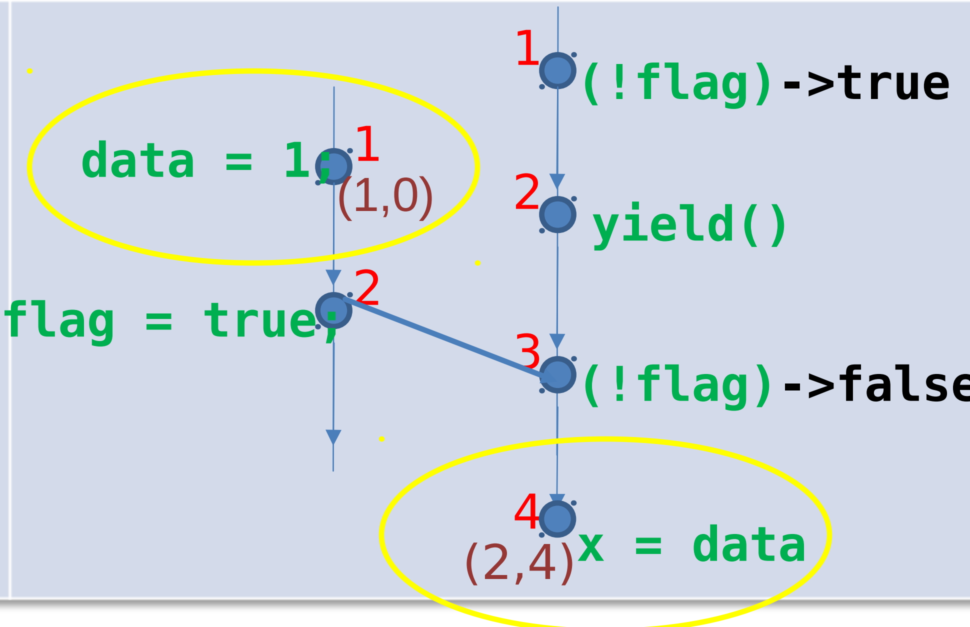
Thread 1

```
data = 1;
flag = true;
```

Thread 2

```
while (!flag)
    yield();
int x = data;
```

Dynamic Execution Trace



- Not a data race because (1,0) ≤ (2,4)
- If flag were not declared volatile, we would not add a cross-edge, and this would be a data race.

Refinement Checking

Concurrent Data Types

- Frequently used building blocks for parallel or concurrent applications.
- Typical examples:
  - Concurrent stack
  - Concurrent queue
  - Concurrent deque
  - Concurrent hashtable
  - ....
- Many slightly different scenarios, implementations, and operations

Correctness Criteria

- Say we are verifying concurrent X
  (for X $\in$ queue, stack, deque, hashtable …)
- Typically, concurrent X is expected to behave like atomically interleaved sequential X
- We can check this without knowing the semantics of X

Observation Enumeration Method

[CheckFence, PLDI07]

- Given concurrent test:

Stack s = new ConcurrentStack();	
`s.Push(1);`	`b1 = s.Pop(out i1);` `b2 = s.Pop(out i2);`

- (Step 1 : Enumerate Observations)
  Enumerate coarse-grained interleavings and record observations
  1. b1=true i1=1 b2=false i2=0
  2. b1=false i1=0 b2=true i2=1
  3. b1=false i1=0 b2=false i2=0
- (Step 2 : Check Observations)
  Check refinement: all concurrent executions must look like one of the recorded observations

Conclusion

- CHESS is a tool for
  - Systematically enumerating thread interleavings
  - Reliably reproducing concurrent executions
- Coverage of Win32 and .NET API
  - Isolates the search & monitor algorithms from their complexity
- CHESS is extensible
  - Monitors for analyzing concurrent executions