CHESS: Analysis and Testing of Concurrent Programs

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What you will learn in this tutorial

- Difficulties of testing/debugging multithreaded programs
- CHESS – verifier for multi-threaded programs
  - Provides systematic coverage of thread interleavings
  - Provides replay capability for easy debugging
- CHESS algorithms
- Types of concurrency errors, including data races
- How to extend CHESS
  - CHESS monitors

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

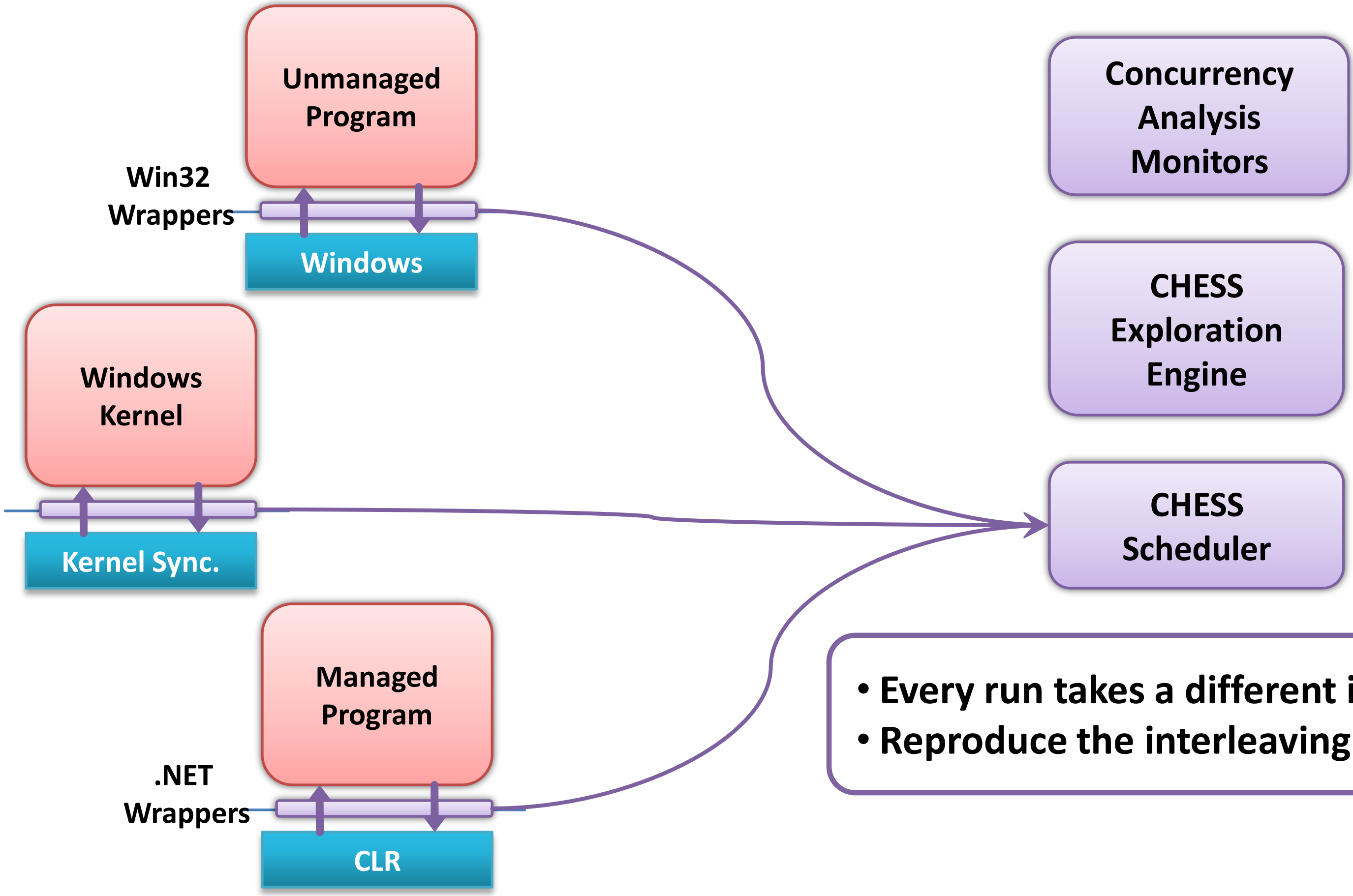
CHESS in a nutshell

- 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 Demo

- Find a simple Heisenbug

CHESS Architecture



Unmanaged Program

Win32 Wrappers

Windows

Windows Kernel

Kernel Sync.

Managed Program

.NET Wrappers

CLR

Concurrency Analysis Monitors

CHESS Exploration Engine

CHESS Scheduler

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

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
- Generality of Specifications
  - Find interesting classes of concurrency errors
  - Safety and liveness

Comparison with other approaches to verification

	Model Checking	Static Analysis	CHESS
Scalability	+	++	++
Precision	+	+	++
Coverage	++	++	+
Generality	++	+	++

Errors that CHESS can find

- Assertions in the code
- Any dynamic monitor that you run
  - Memory leaks, double-free detector, …
- Deadlocks
  - Program enters a state where no thread is enabled
- Livelocks
  - Program runs for a long time without making progress
- Dataraces
- Memory model races

CHESS Scheduler

Concurrent Executions are Nondeterministic

Thread 1

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

Thread 2

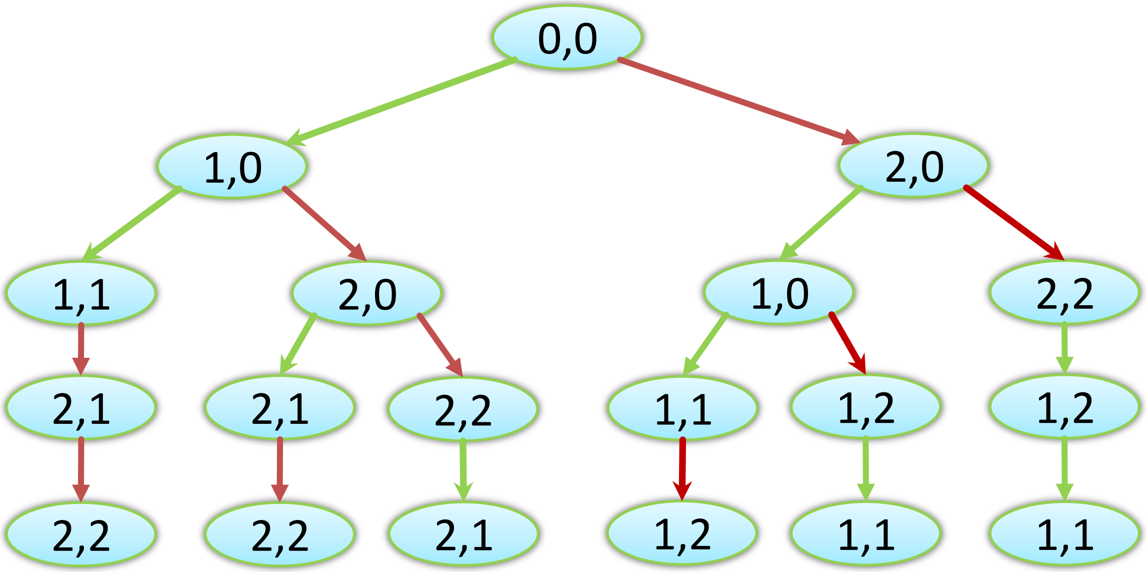
```
x = 2;
y = 2;
```

`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

Sources of Nondeterminism

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- 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
- 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

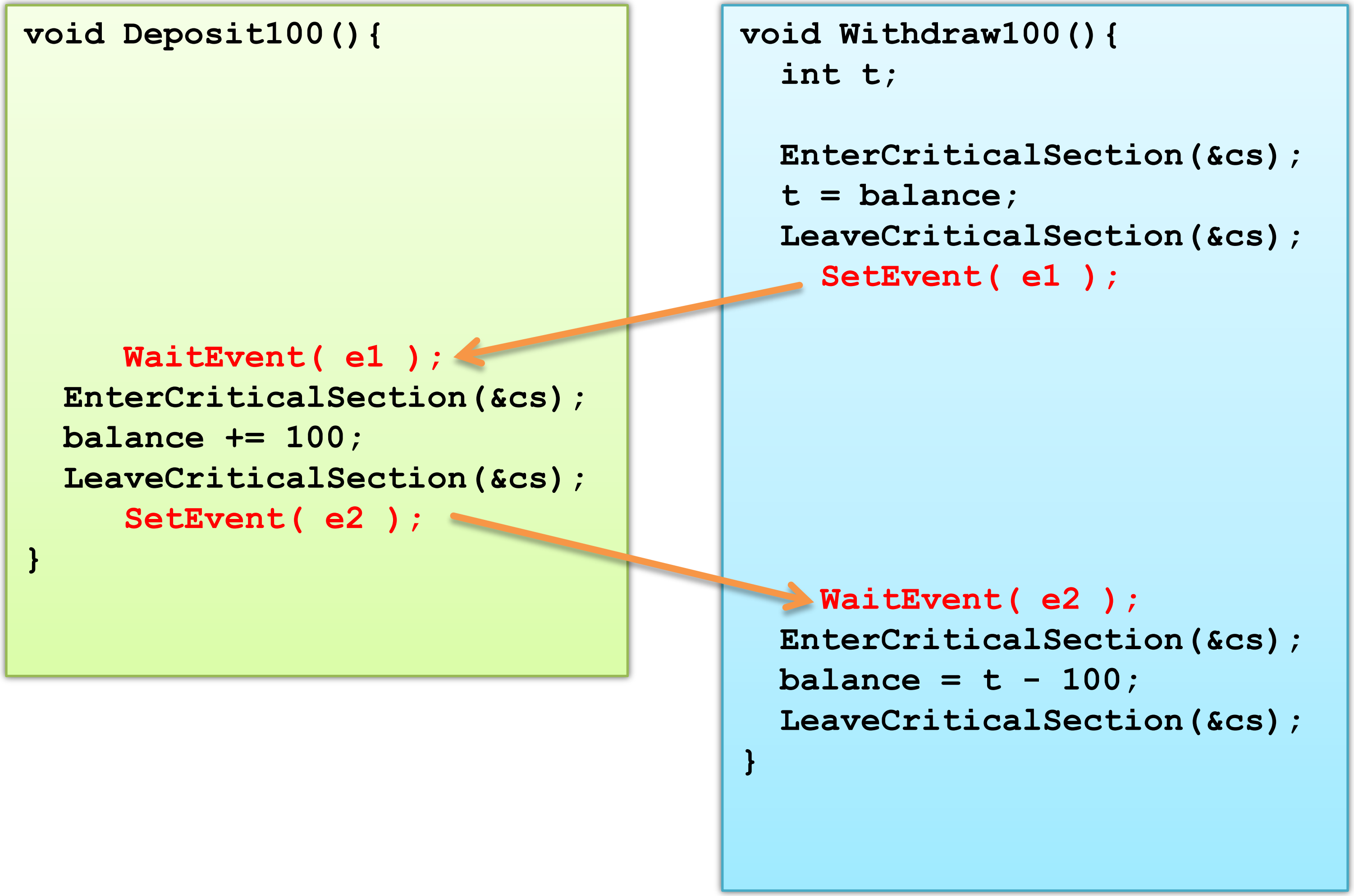
Deposit Thread

```
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);

}
```

Introduce Predictable Delays with Additional Synchronization



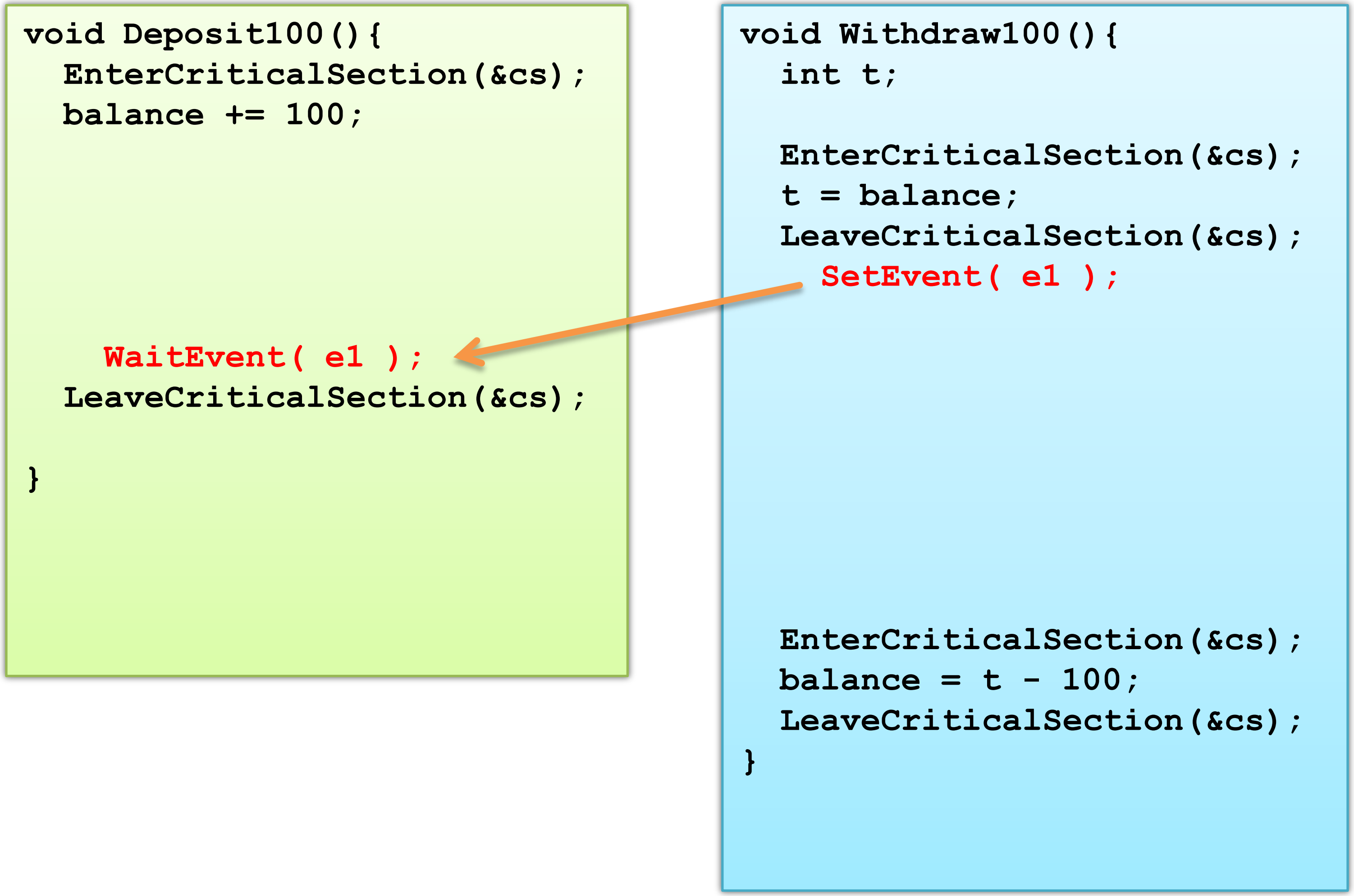
Deposit Thread

```
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 Synchronization Wrappers

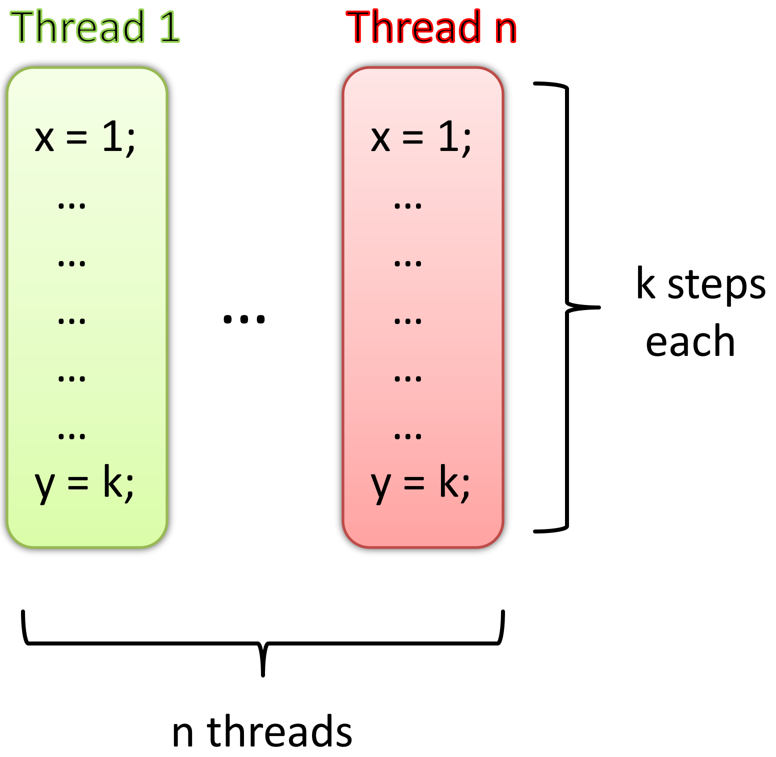
- Understand the semantics of synchronizations
- Provide enabled information

```
CHESS_EnterCS{
  while(true) {
    canBlock = TryEnterCS (&cs);
    if(canBlock)
       Sched.Disable(currThread);
  }
}
```

- Expose nondeterministic choices
    - An asynchronous ReadFile can possibly return synchronously

CHESS Algorithms

State space explosion



Thread 1

x = 1;
…
…
…
…
…
y = k;

…

Thread n

x = 1;
…
…
…
…
…
y = k;

k steps each

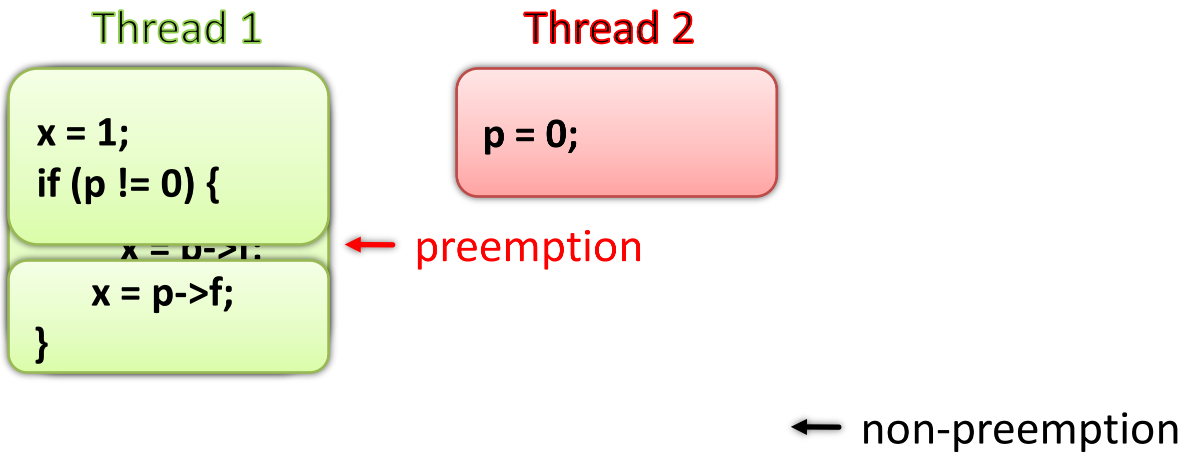
n threads

- 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



Thread 1

```
x = 1;
if (p != 0) {
    x = p->f;
}
```

Thread 2

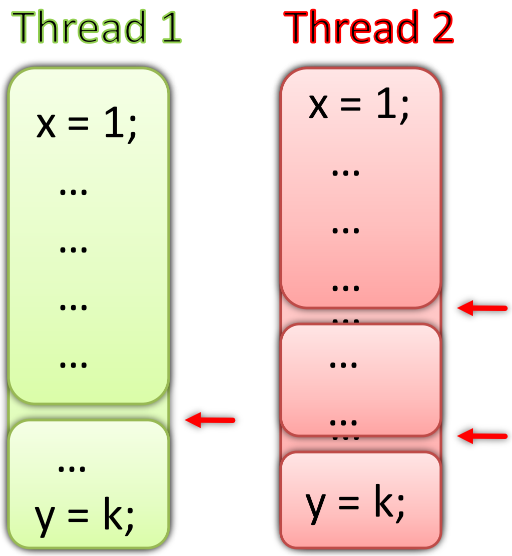
```
p = 0;
```

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



Thread 1

x = 1;
…
…
…
…
…
y = k;

Thread 2

x = 1;
…
…
…
…
…
…
…
y = k;

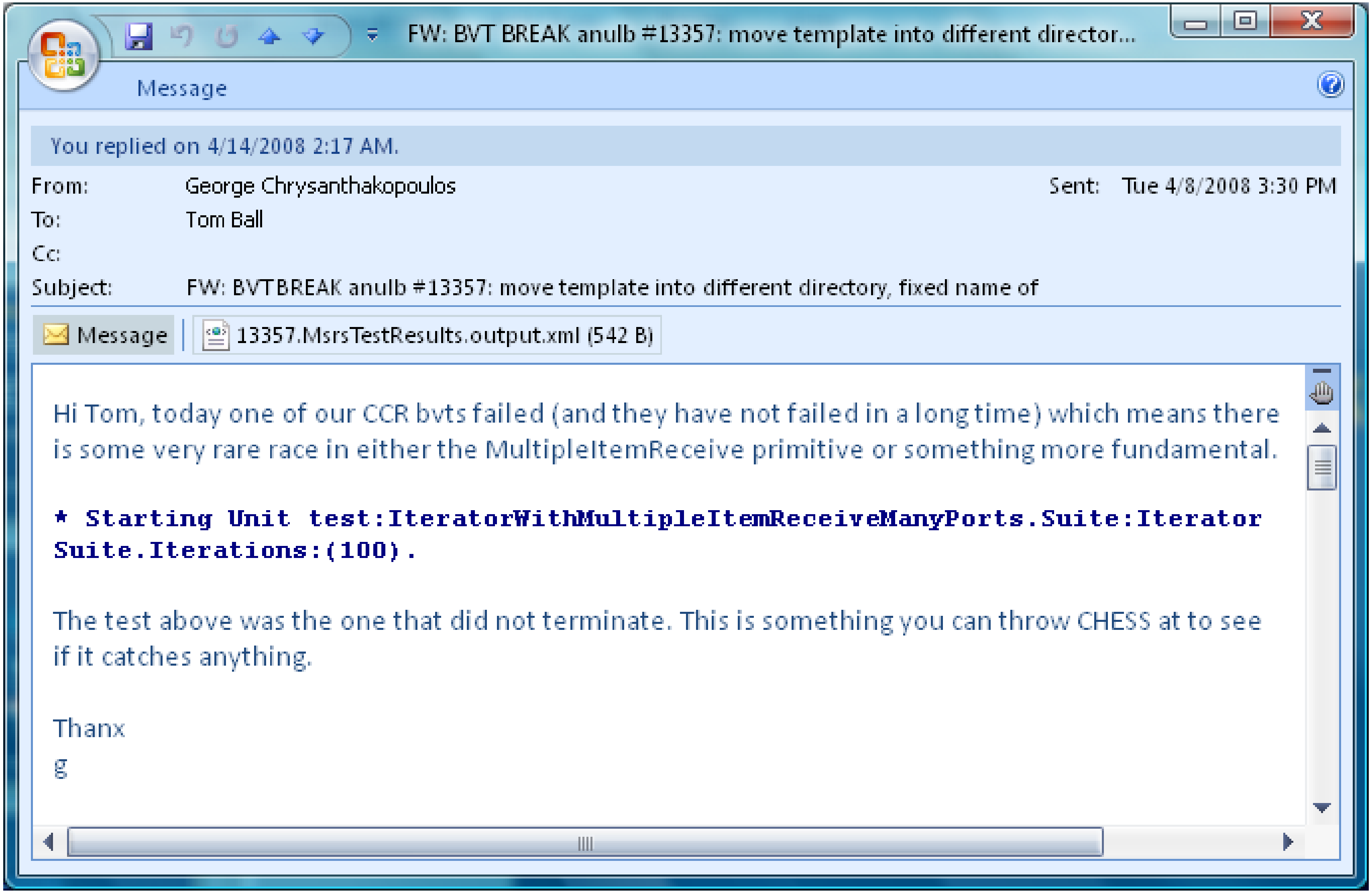
- Choose c preemption points
- Permute n+c atomic blocks

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

Finding and reproducing CCR Heisenbug

George Chrysanthakopoulos' Challenge



You replied on 4/14/2008 2:17 AM.

From: George Chrysanthakopoulos
Sent: Tue 4/8/2008 3:30 PM
To: Tom Ball
Cc:
Subject: FW: BVTBREAK anulb #13357: move template into different directory, fixed name of

Hi Tom, today one of our CCR bvts failed (and they have not failed in a long time) which means there is some very rare race in either the MultipleItemReceive primitive or something more fundamental.

```
* Starting Unit test:IteratorWithMultipleItemReceiveManyPorts.Suite:Iterator
Suite.Iterations:(100).
```

The test above was the one that did not terminate. This is something you can throw CHESS at to see if it catches anything.

Thanx
g

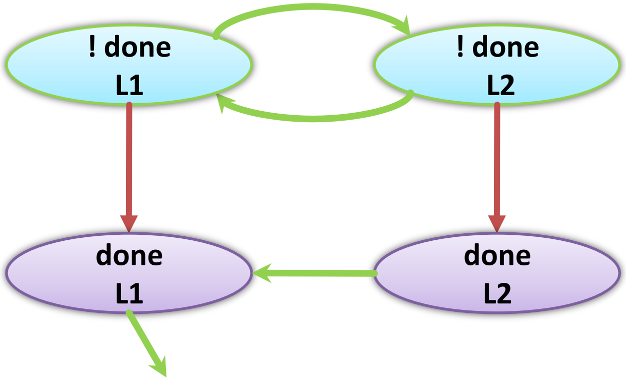
Concurrent programs have cyclic state spaces

Thread 1

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

Thread 2

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



- Spinlocks
- Non-blocking algorithms
- Implementations of synchronization primitives
- Periodic timers
- …

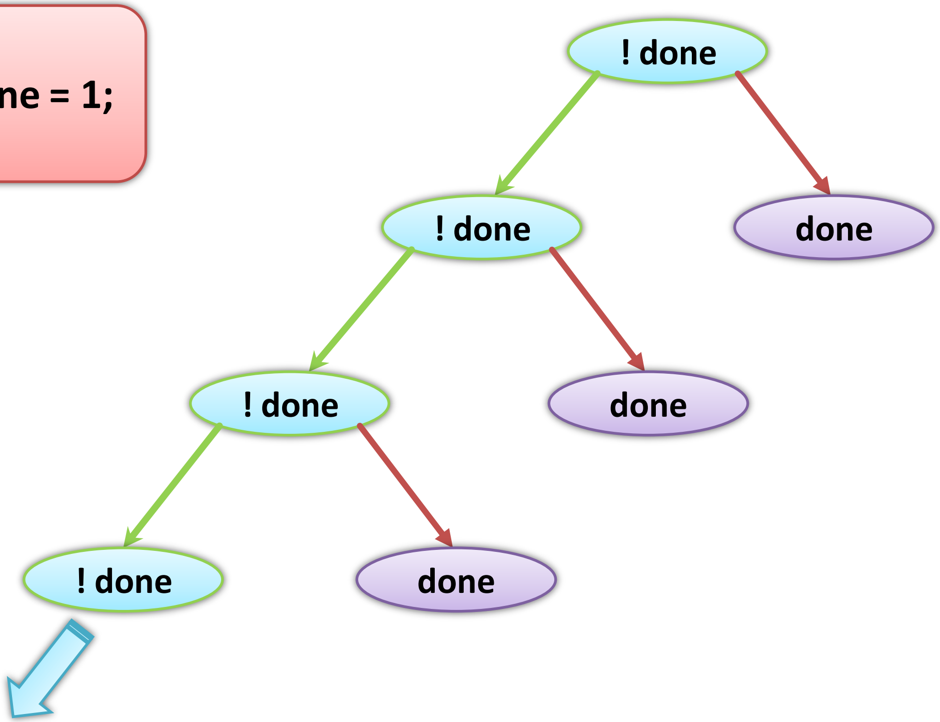
A demonic scheduler unrolls any cycle ad-infinitum

Thread 1

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

Thread 2

```
done = 1;
```



! done

! done

done

! done

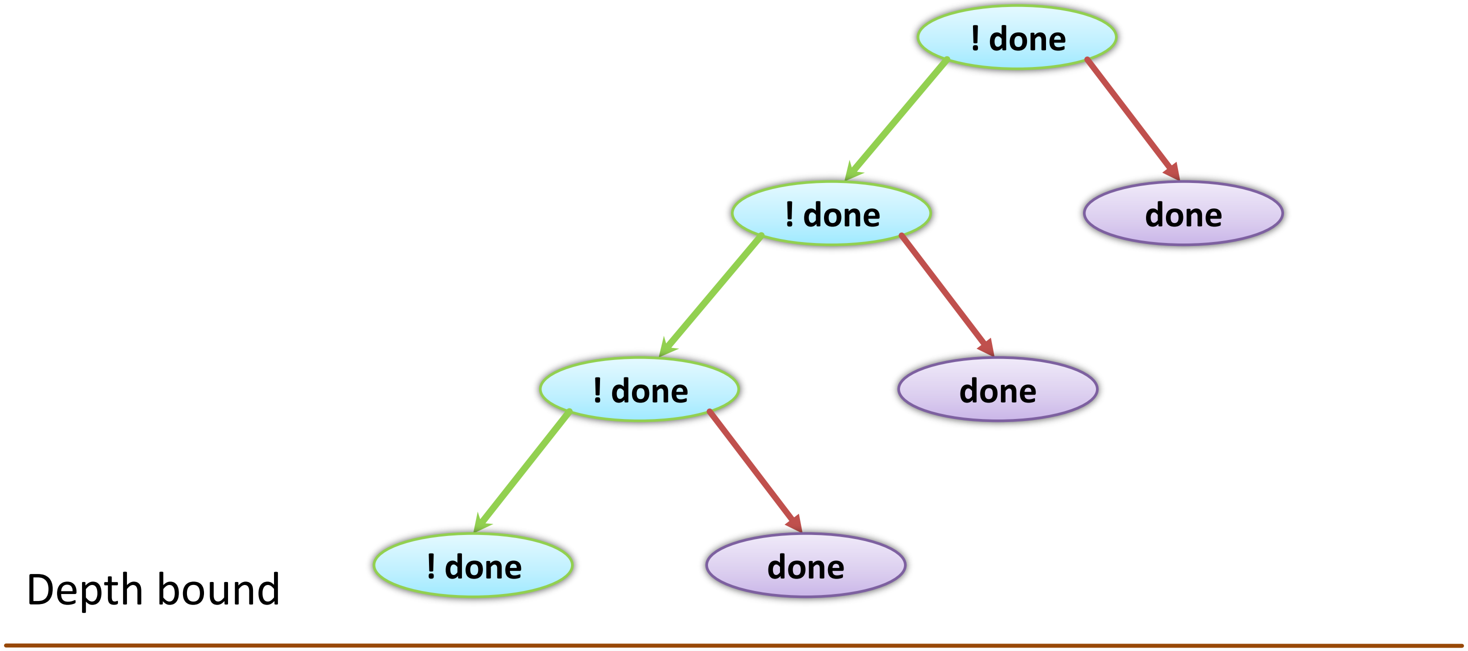
done

! done

done

Depth bounding

- Prune executions beyond a bounded number of steps



! done

! done

done

! done

done

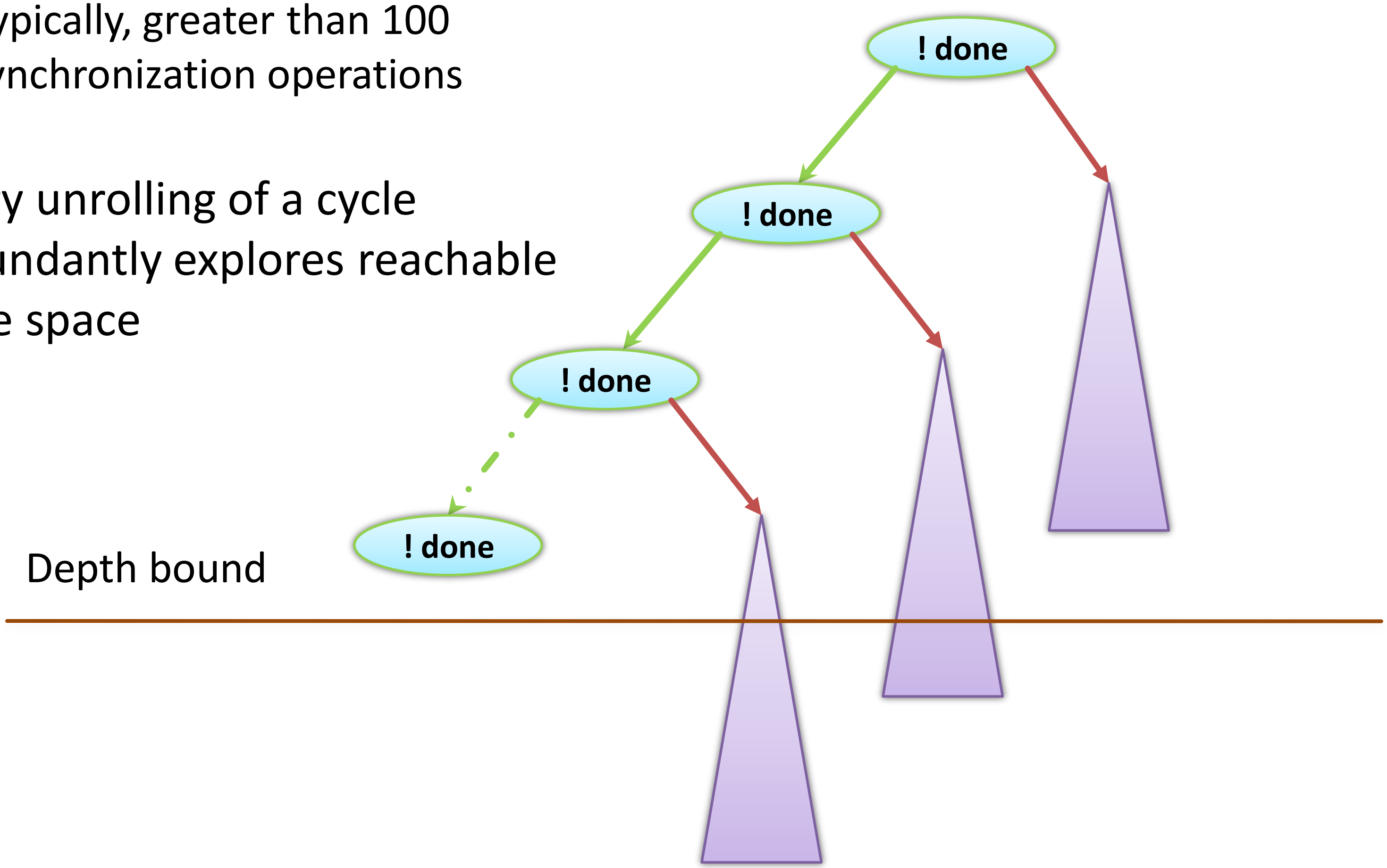
Depth bound

! done

done

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;
```

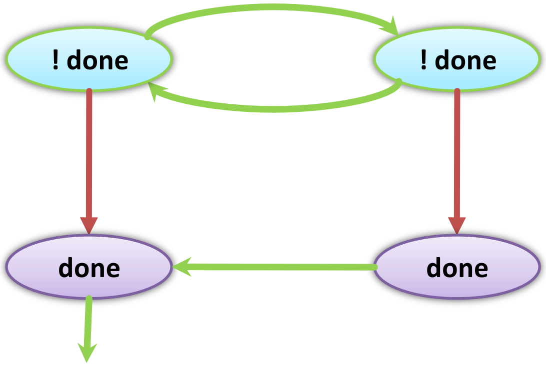
Key idea

Thread 1

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

Thread 2

```
done = 1;
```

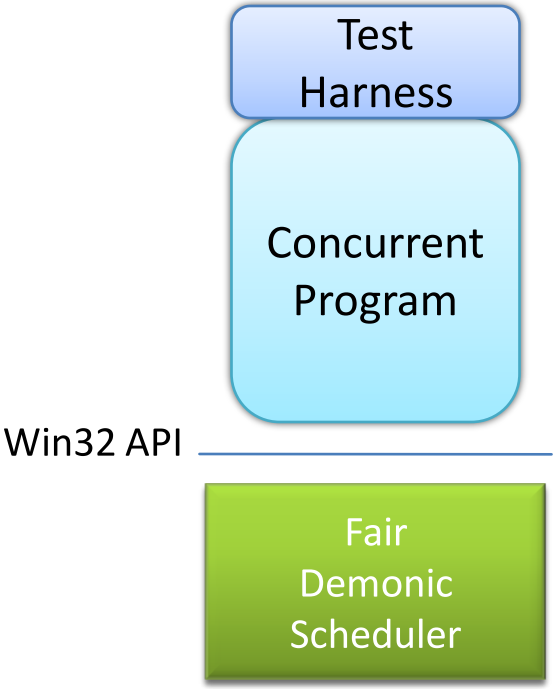


- This test terminates only when the scheduler is fair
- Fairness is assumed by programmers

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

- Forall t :: GF (enabled(t) → scheduled(t))
- 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

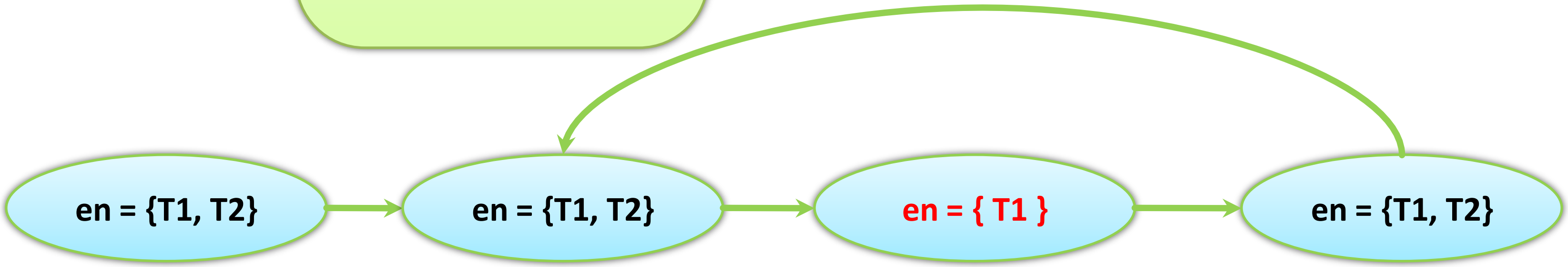
Weak fairness does not suffice

Thread 1

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

Thread 2

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



T1: Sleep()
T2: Lock(l)

T1: Lock(l)
T2: Lock(l)

T1: Unlock(l)
T2: Lock(l)

T1: Sleep()
T2: Lock(l)

Strong Fairness

- Forall t :: GF enabled(t) → GF scheduled(t)
- 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

- Apt & Olderog ’83
  - 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)
- Do it without capturing the program states

(Good) Programs indicate lack of progress

Thread 1

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

Thread 2

```
done = 1;
```

- Good Samaritan assumption:
  - Forall threads t : GF scheduled(t) → GF yield(t)
  - A thread when scheduled infinitely often yields the processor infinitely often
- Examples of yield:
  - Sleep(), ScheduleThread(), asm {rep nop;}
  - Thread completion

Robustness of the Good Samaritan assumption

- A violation of the Good Samaritan assumption is a performance error

Thread 1

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

Thread 2

```
done = 1;
```

- Programs are parsimonious in the use of yields
  - A Sleep() almost always indicates a lack of progress
  - Implies that the thread is stuck in a state-space cycle

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
  - Scheduler is fully demonic on yield-free paths
  - 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

Four outcomes of the semi-algorithm

- Terminates without finding any errors
- Terminates with a safety violation
- Diverges with an infinite execution
  - that violates the GS assumption (a performance error)
  - that is strongly-fair (a livelock)

- In practice: detect infinite executions by a very long execution

Data Races & Memory Model 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, use an interlocked operation, or declare a variable volatile.
  - Racy programs risk obscure failures caused by memory model relaxations in the hardware and the compiler
  - But: many programmers tolerate “benign” races

- Race-free programs are easier to verify
  - if 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

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

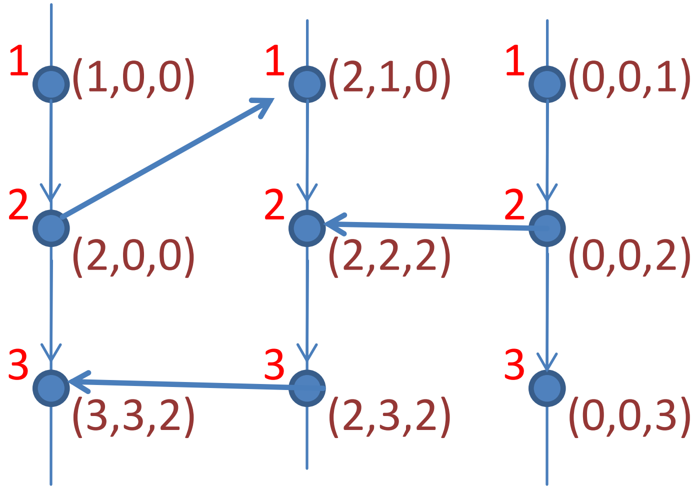
Thread 2

```
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
    - System calls (asynchronous IO)
    - Etc.

Example

Static Program

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

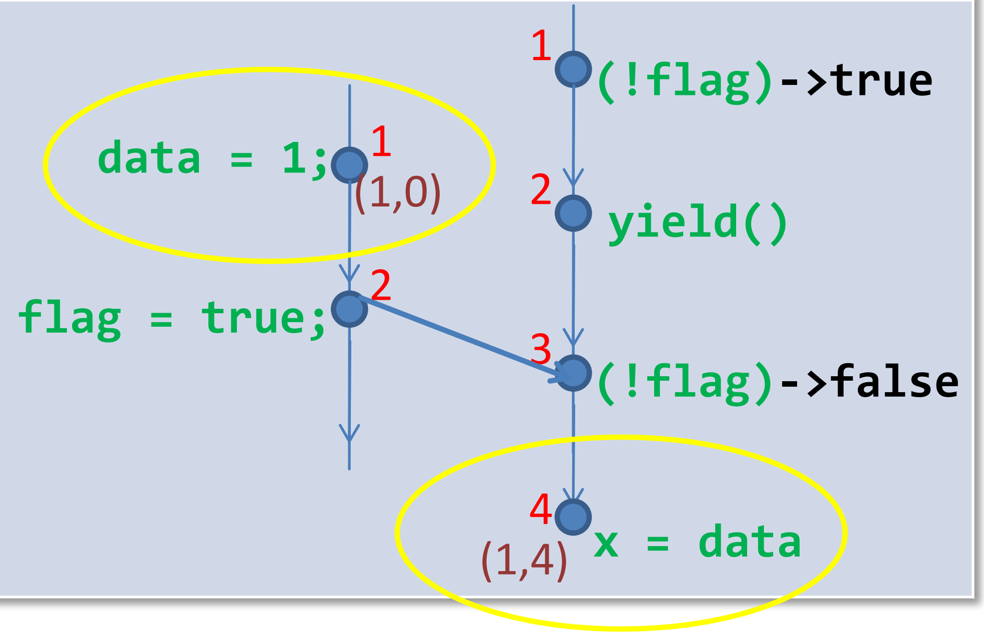
Thread 1

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

Thread 2

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

Dynamic Execution Trace



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

Basic Algorithm

- For each explored schedule,
  - Execute code and timestamp all data accesses.
  - Check if there were any conflicting concurrent accesses to some location.

- This basic algorithm can be optimized in many ways
  - On-the-fly checking, Memory management
  - Lightweight alternatives to full vector clocks
  - See [Flanagan PLDI 09]

Reduction for Race-Free Programs

- By default, CHESS preempts on synchronization accesses only
  - May miss bugs if program contains data race

- If we turn on race detection, CHESS can verify that the reduction is sound by verifying absence of data races.

- Thus, for race-free programs, we get both:
  - Full guarantee
  - Reduction in the number of schedules

Preemption / Instrumentation Level

- Speed/coverage tradeoff : choose mode

	Sync only	**Sync. + vol. (Default)**	**Sync + vol. + Race Detection**	**All accesses**
Locks, Events, Interlocked, etc.	Instrumented & Preempted	Instrumented & Preempted	Instrumented & Preempted	Instrumented & Preempted
Volatile Accesses	-	Instrumented & Preempted	Instrumented & Preempted	Instrumented & Preempted
All Data Accesses	-	-	Instrumented	Instrumented & Preempted

Demos: SimpleBank / CCR

- Find a simple data race in a toy example
- Find a not-so-simple data race in production code

Bugs Caused By Relaxed Memory Models

- Programmers avoid locks in performance-critical code
  - Faster to use normal loads and stores, or interlocked operations
- Low-lock code can break on **relaxed memory models**
  - Most multicore machines (including x86) do not guarantee sequential consistency of memory accesses

- Vulnerabilities are hard to find, reproduce, and analyze
  - Show up only on multiprocessors
  - Often not reproduceable

Example: Store Buffers Break Dekker

- On an ideal (sequentially consistent) multiprocessor, this code never executes foo() and bar() at the same time

```
volatile int A;
volatile int B;

 Thread 1            Thread 2
 ---------           ---------
 A = 1;              B = 1;
 If (B == 0)         If (A == 0)
   foo();              bar();
```

- But on x86 (and almost all other multiprocessors), it may, because of store buffers.

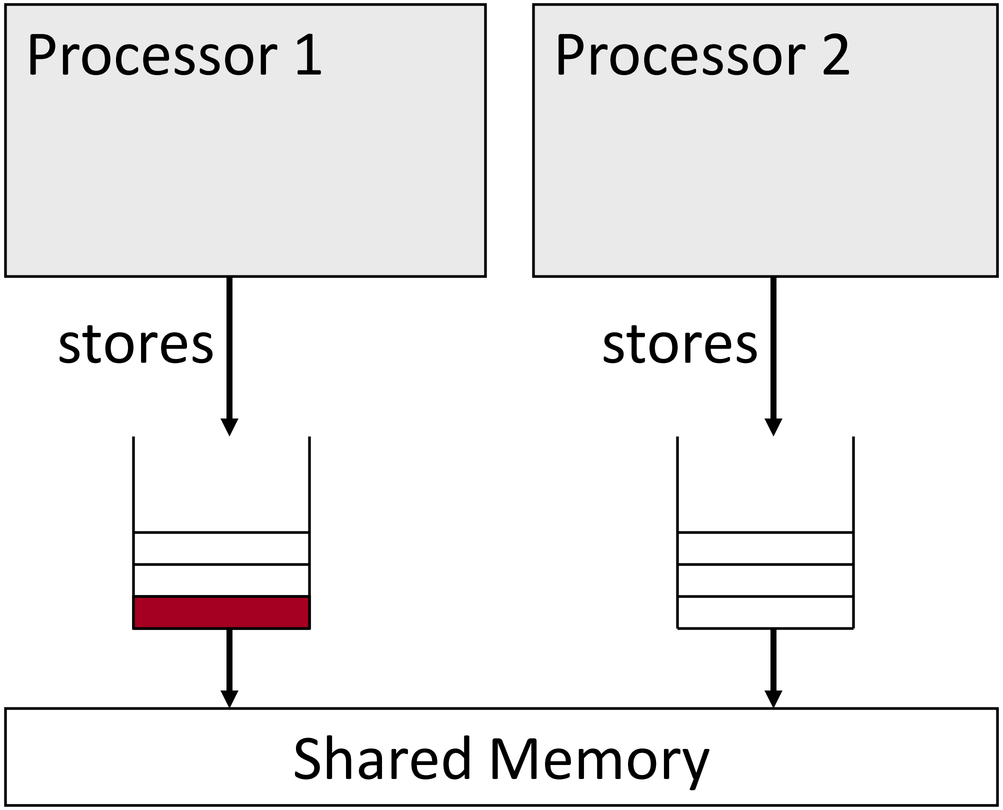
Memory Access Terminology

C++	Java	C#
atomic	volatile	interlocked
low-level atomic	-	volatile
volatile	-	-
(regular)	(regular)	(regular)

- Code using accesses marked red for synchronization purposes is susceptible to store buffer bugs.

Store Buffers

- Each processor buffers its own writes in a FIFO store buffer
- Remote processors do not see the buffered write until it is committed to shared memory
- Local processor "snoops" its own buffer when reading from memory
- Important for hardware performance



How to Find Store Buffer Bugs?

- Naïve: simulate machine
  - Too many schedules.
- Better: build a *borderline monitor* [CAV 2008].

Idea: While exploring schedules under CHESS, check for *stale loads*.

- A *stale load* is a load that may return a value under TSO that it could never return under SC.
- [Thm.] A program is TSO-safe if and only if all executions are free of stale loads.

Demos: Dekker / PFX

- Basic test: Dekker
- Found 2 dekker-like synchronization errors in production code
  - “optimization” of signal-wait pattern
  - Double-ended work-stealing queue

```
volatile bool isIdling;
volatile bool hasWork;

   //Consumer thread
   void BlockOnIdle(){
      lock (condVariable){
         isIdling = true;
         if (!hasWork)
             Monitor.Wait(condVariable);
         isIdling = false;
      }
   }

   //Producer thread
   void NotifyPotentialWork(){
      hasWork = true;
      if (isIdling)
        lock (condVariable) {
           Monitor.Pulse(condVariable);
        }
   }
```

Store Buffer Bugs - Experience

- Relatively rare… found only 3 so far
  - We expect to find more as we cover more code… detection is on by default whenever race detection is on
  - Found 1 false positive so far (i.e. “benign” stale load).

- Very common for certain algorithms, e.g. work stealing queue
  - We found one in PFX work-stealing queue
  - Know of 4 other teams (inside & outside Microsoft) who faced store buffer issues when implementing work-stealing queue

Writing a CHESS Monitor

Specifications?

- We have not seen significant practical success of verification methodology that requires extensive formal specification.

- More pragmatic: monitor certain or likely indicators automatically. Currently, we…
  - …flag error on: Deadlock, Livelock, Assertion Violation.
  - …generate warnings for: Data races, Stale loads.

More Monitors Find More Bugs

- Use runtime monitors for ‘typical programmer mistakes’
  - Data Races, Stale Loads (✓)
  - Atomicity violations, High-level Data Races
  - Incorrect API usage (for all kinds of APIs), e.g. Memory Leaks
- Much existing research on runtime monitors
- **CHESS SDK** provides infrastructure, you write your own monitor.

Monitors Benefit from Infrastructure

- Instrumentation
  - For both C# and C/C++
- Abstraction
  - Threads, synchronization & data variables, events
- Sequential schedule
  - Monitors need not worry about concurrent callbacks
- Repro capability
  - Any errors found can be reproduced deterministically
- Schedule enumeration
  - Enumerates schedules using reductions & heuristics
  - turns runtime monitors into verification tools

Chess <-> Monitor interface

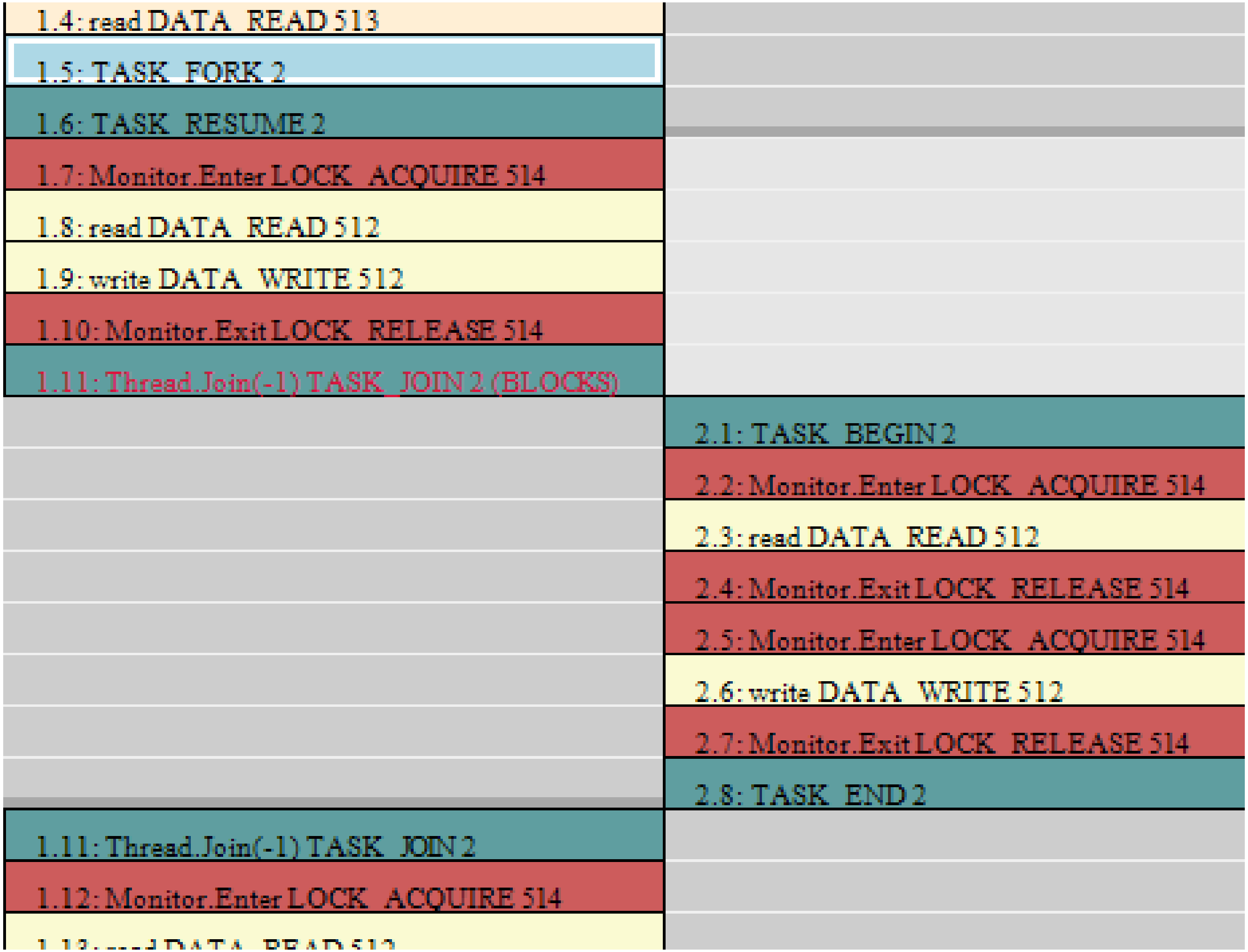
- Each monitor gets called by CHESS repeatedly
  - … at beginning and end of each schedule
  - … on relevant program events
    - Synchronization operations
    - Data variable accesses
    - User-defined instrumentation

- Callbacks abstract many low-level details
  - Handle plethora of synchronization APIs and concurrency constructs under the covers

Abstractions Provided

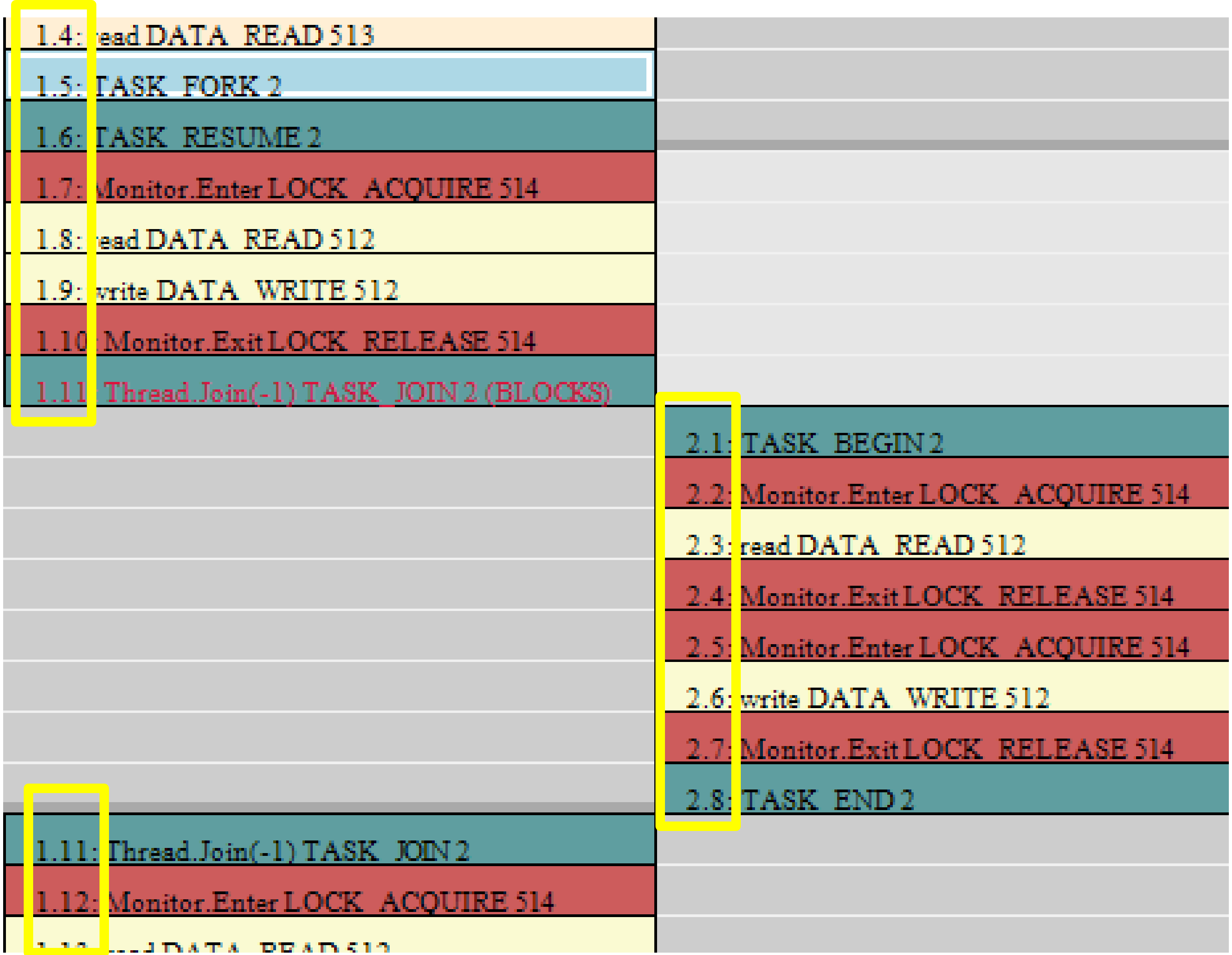
- Thread id = integer
  - Chess numbers threads consecutively 1, 2, 3, ….
- Event id = integer x integer
  - Chess numbers events in each thread consecutively 1.1, 1.2, 1.3, …. 2.1., 2.2., 2.3, …
- Syncvar = integer
  - Abstractly represents a synchronization object (lock, volatile variable, etc.)
- SyncvarOp = { LOCK_ACQUIRE, LOCK_RELEASE, RWVAR_READWRITE, RWVAR_READ, RWVAR_WRITE, TASK_FORK, TASK_JOIN, TASK_START, TASK_RESUME, TASK_END, …}
  - Represents synchronization operation on syncvar

ConcurrencyExplorer View of Schedule



1.4: read DATA_READ 513	
1.5: TASK_FORK 2	
1.6: TASK_RESUME 2	
1.7: Monitor.Enter LOCK_ACQUIRE 514	
1.8: read DATA_READ 512	
1.9: write DATA_WRITE 512	
1.10: Monitor.Exit LOCK_RELEASE 514	
1.11: Thread.Join(-1) TASK_JOIN 2 (BLOCKS)	
	2.1: TASK_BEGIN 2
	2.2: Monitor.Enter LOCK_ACQUIRE 514
	2.3: read DATA_READ 512
	2.4: Monitor.Exit LOCK_RELEASE 514
	2.5: Monitor.Enter LOCK_ACQUIRE 514
	2.6: write DATA_WRITE 512
	2.7: Monitor.Exit LOCK_RELEASE 514
	2.8: TASK_END 2
1.11: Thread.Join(-1) TASK_JOIN 2	
1.12: Monitor.Enter LOCK_ACQUIRE 514	
1.13: read DATA_READ 512	

Event IDs



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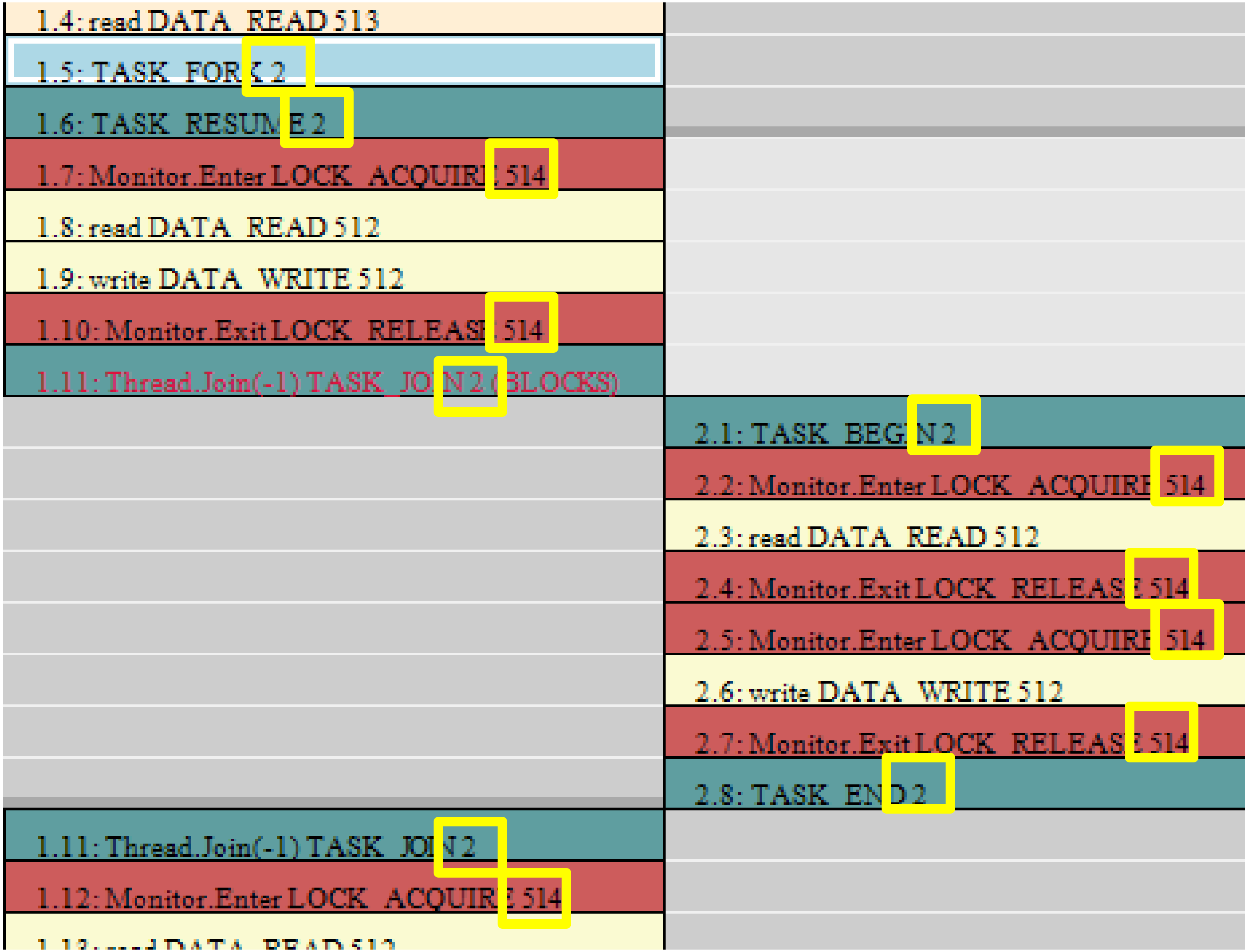
SyncVar



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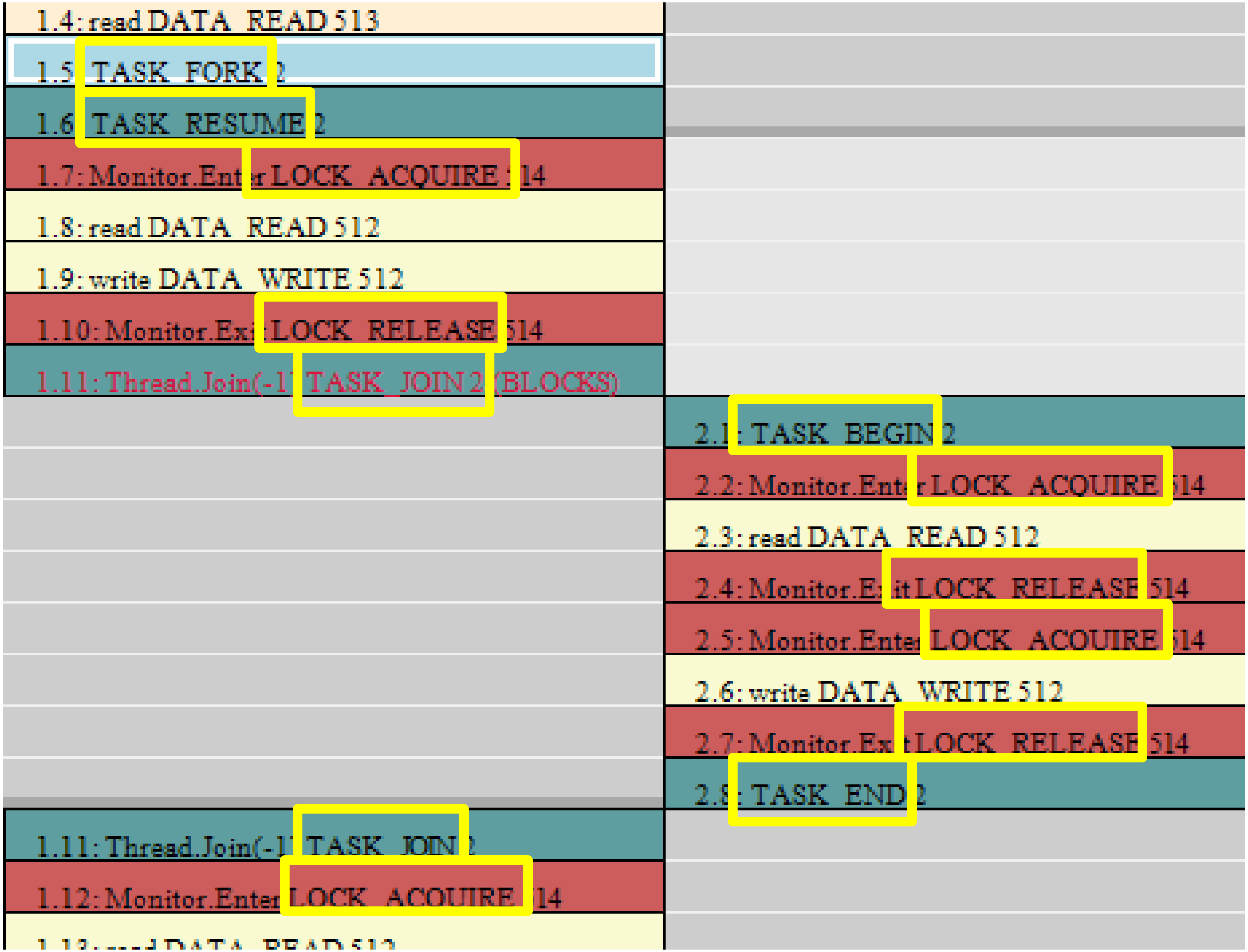
SyncVarOp



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1.13: read DATA_READ 512

Some Callbacks

- At beginning & end of schedule

```
virtual void OnExecutionBegin(IChessExecution* exec)
virtual void OnExecutionEnd(IChessExecution* exec)
```

- Right after a synchronization operation:

```
virtual void OnSyncVarAccess(EventId id, Task tid,
                              SyncVar var, SyncVarOp op, size_t sid)
```

- Right after a data access:

```
virtual void OnDataVarAccess(EventId id, void* loc, int
                              size, bool isWrite, size_t pcId)
```

- Right before a synchronization operation:

```
virtual void OnSchedulePoint(EventId id, SyncVar var,
                                       SyncVarOp op, size_t sid)
```

Happens-before information

- Can query ‘character’ of a sync var op

```
static bool IsWrite(SyncVarOp op)
static bool IsRead(SyncVarOp op)
```

- Get happens-before edges between two sync-var ops
  - To the same variables
  - At least one of which is a write
- Note: most syncvarops are considered to be both reads & writes

Reduction-Compatible Monitors

- Different schedules may produce same hb-execution
  - Call such schedules hb-equivalent
- Program behaves identically under hb-equivalent schedules
  - Thus, reductions are sound (sleep-sets, data-race-free)
- But: some monitors may not behave equivalently
  - E.g. naïve race detection may require specific schedule
  - For coverage guarantees, monitor must be reduction-compatible: must detect error on all hb-equivalent schedules
- Our Race Detection and Store Buffer Detection are Reduction -Compatible

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
- Written by experts… but the experts need help

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
- Implement easy to use, automatic consistency check

Observation Enumeration Method

[CheckFence, PLDI07]

- Given concurrent test, e.g.

```
          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

Demo

- Show refinement checking on simple stack example

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
  - Future: Strategies for exploring the state space