Concurrency Unit Testing

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Concurrent programming is HARD

- Concurrent executions are highly nondeterministic
- 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

Concurrency unit testing (I)

- Concurrency unit test
  - initializes the module
  - creates few threads each performing a few operations
- Systematically explore all interactions of these threads
- Small-scope hypothesis
  - bugs manifest in corner cases of relatively small scenarios
  - validated by years of research in model checking

Concurrency unit testing (II)

- Dynamic
  - Concrete initial state and thread inputs
  - Concrete runtime (libraries/OS/hardware)
  - Execute program along many different schedules

- Static
  - Symbolic initial state and thread inputs
  - Abstract model of runtime (libraries/OS/hardware)
  - Represent behavior for many different schedules as a single logical formula
  - Solve formula using an automated theorem prover

CHESS

Joint work with

Tom Ball
Sebastian Burckhardt
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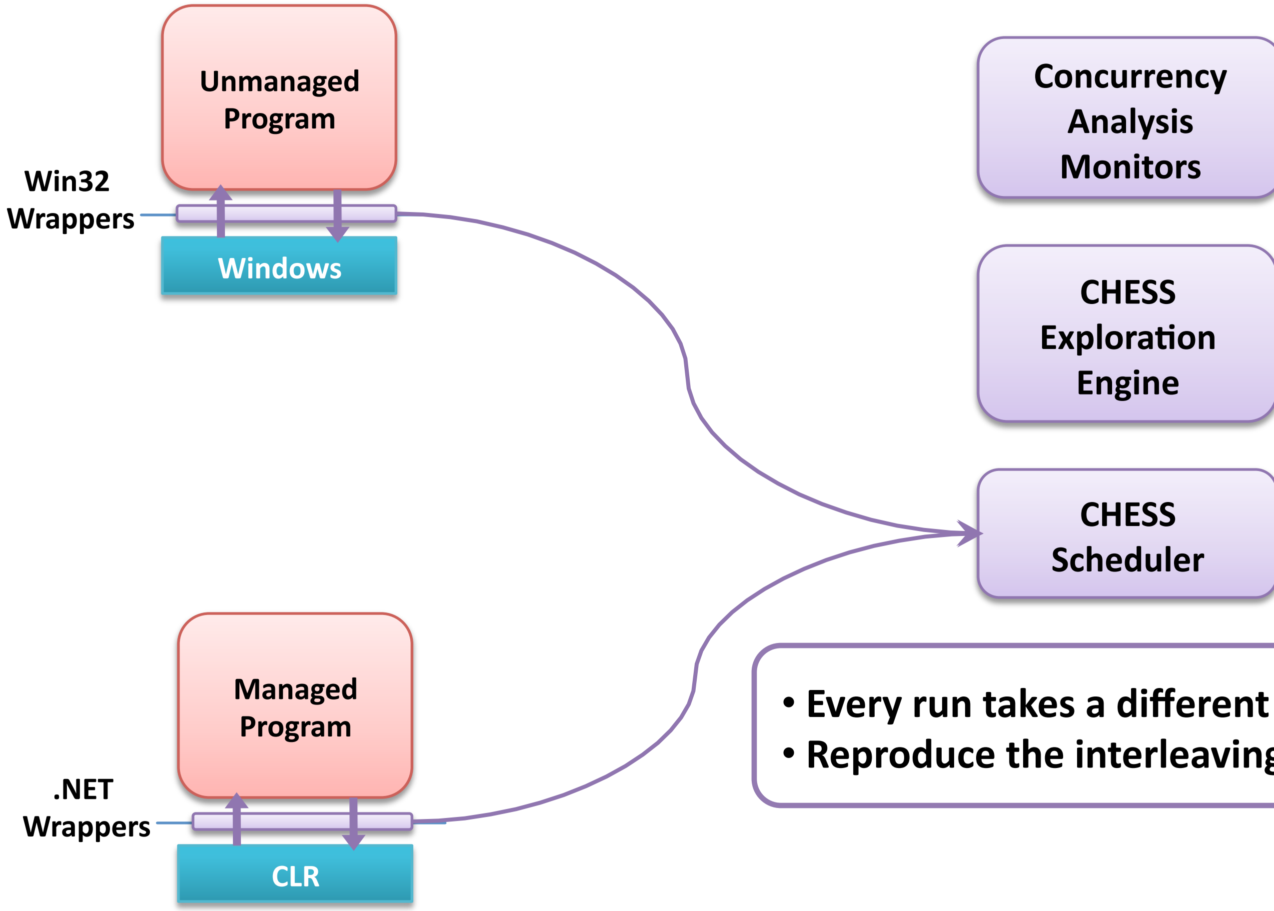
CHESS in a nutshell



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

CHESS monitors

- 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

- 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

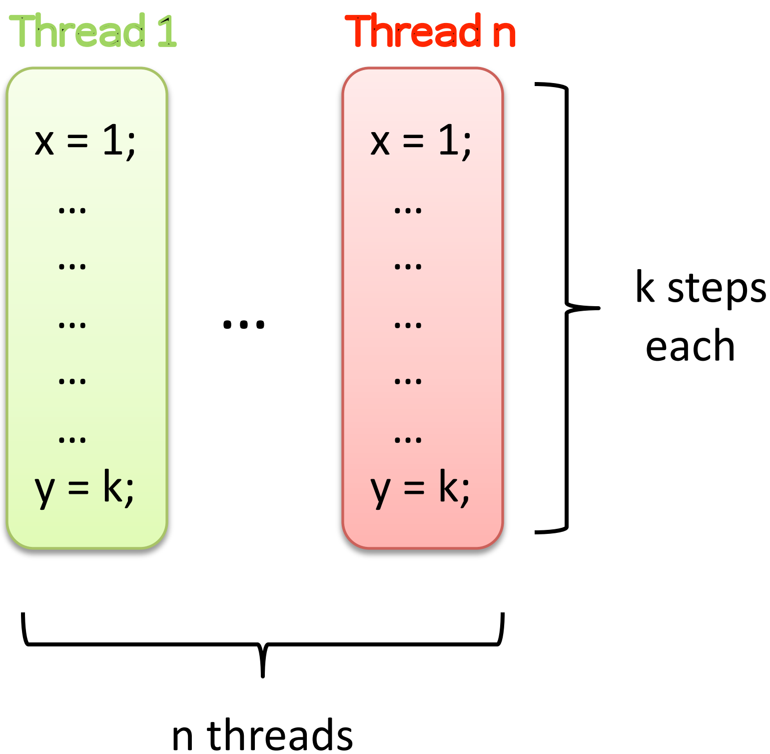
CHESS synchronization wrappers

- 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

State space explosion



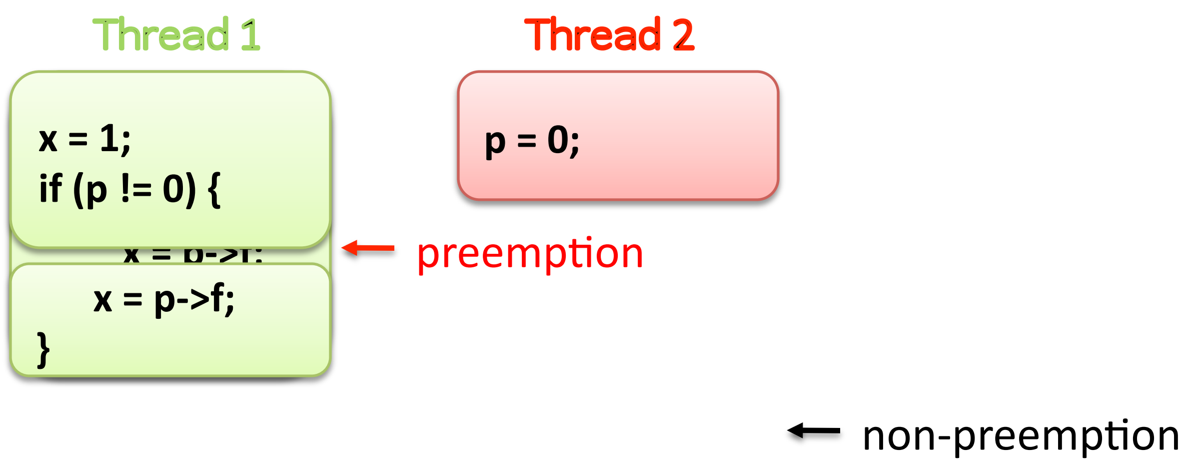
- Number of executions $= O(n^{nk})$
- Exponential in both n and k
  - Typically: $n < 10 \quad k > 100$
- Limits scalability to large programs

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

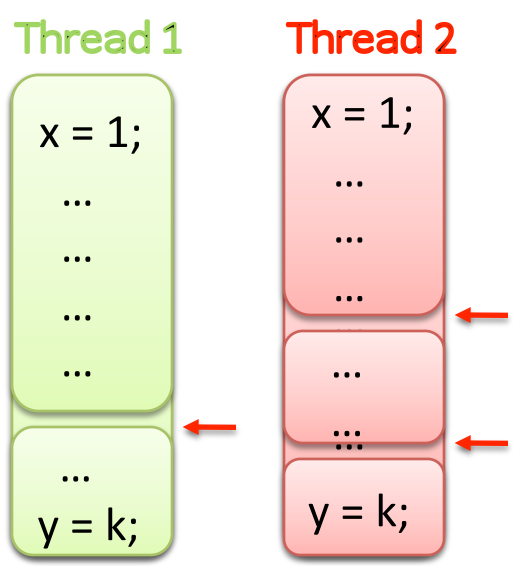


Polynomial state space

- 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

- Many errors are caused by few (<2) preemptions
- Generates an easy to understand error trace
  - Preemption points point to the root-cause of the bug
- A good coverage guarantee to the user
  - When CHESS finishes exploration with 2 preemptions, any remaining bug requires 3 preemptions or more
- Leads to the heuristic of preemption sealing
  - Seal preemptions in libraries to improve scalability
  - Seal preemptions to find multiple errors in single test run

CHESS status

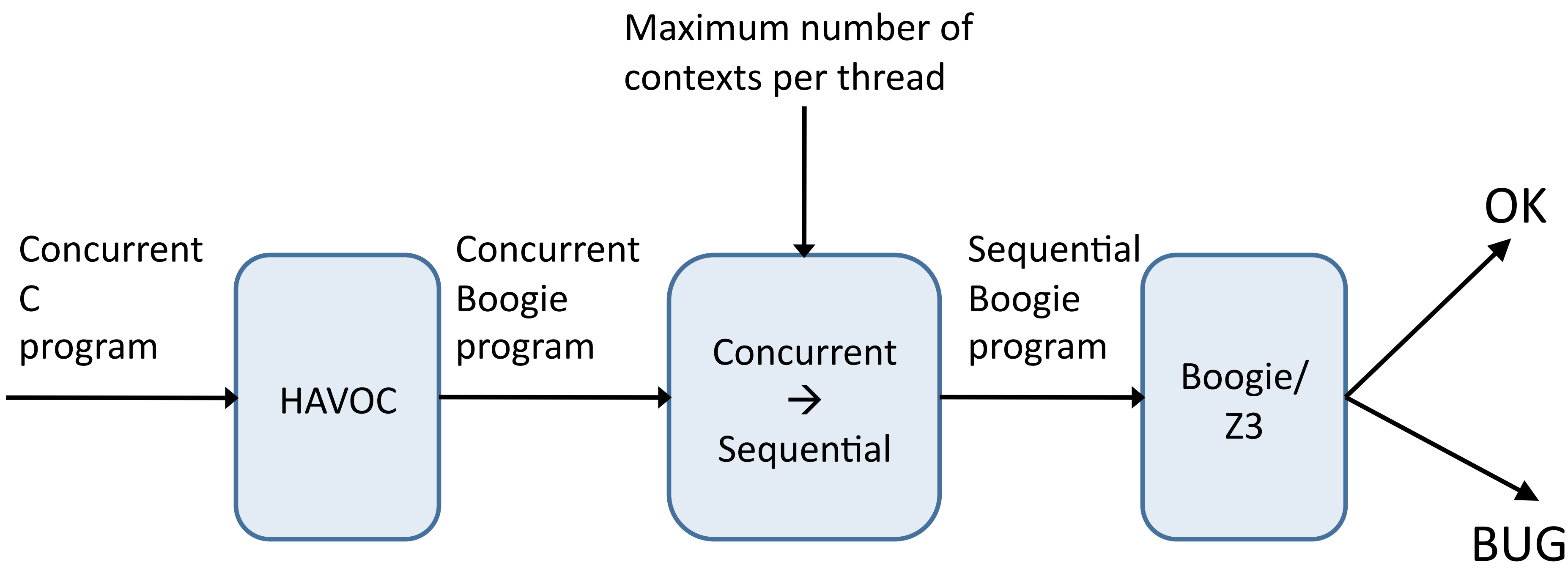
- Publicly available at
  - http://research.microsoft.com/projects/chess
- Basis for Concurrency Curriculum
  - Tom Ball (Microsoft Research)
  - Ganesh Gopalakrishnan (University of Utah)
- Being used by Microsoft product groups
  - Parallel Computing Platform
  - Windows Mobile
- Being used by other companies as well

STORM

Joint work with

Shuvendu Lahiri
Zvonimir Rakamaric

STORM in a nutshell



Concurrent C program→ Concurrent Boogie program

- Systems code written in C is messy
  - Heap, structures, fields
  - Pointers, pointer arithmetic, internal pointers
  - Dynamic memory allocation
  - Casts
- Boogie programs only have scalars and maps
  - easier to convert into formulas

Concurrent Boogie program → Sequential Boogie program

N contexts per thread, shared variable g

$T_1 \mid\mid T_2$

assert *F*

int g_1, g_2,…g_N, v_1,…v_N;
int k := 1;
assume ($g_1 = v_1$ && $g_2 = v_2$ … g [illegible]);

INIT;

L_1: T_1^s;

L_2: T_2^s;

L_3: END;

assert *F*

st → switch(k):
case 1: Schedule; $st[g_1/g]$;
case 2: Schedule; $st[g_2/g]$;
…

assume ($g_1 = v_2$ && $g_2 = v_3$ …);

<u>Schedule</u>
if (*) {k++;}
If (k > N) {k := 1; goto L_{i+1}};

STORM applications

- WDM/KMDF device drivers
  - Correctness of IRP processing

- USB 3.0 device driver stack
  - Co-verification of driver against model of XHCI host controller