Tracing Data Flows to Find Concurrency Errors

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GrammaTech Profile

- Spun out of Cornell
  - › Tim Teitelbaum, CEO and co-founder, Emeritus faculty at Cornell
  - › Tom Reps, President and co-founder, Faculty at U. Wisconsin
- Focus
  - › Program analysis and manipulation
  - › Source and binaries
- Some customers
  - › JPL (site license), Mitre, Draper, NASA, Airbus

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New Tools for Static Concurrency Bug Detection

- Detection of data races
  - DARPA-funded research
- Detection of deadlock and other misuses of locks
  - NASA-funded research
  - In partnership w/ Gerard Holzmann at JPL
    - Power of 10

Agenda

- Why multi-core is important
- Why concurrent programming is hard
- How static analysis can help find concurrency defects

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Soon (almost) All Processors will be Multi-core

- Scaling of single-threaded performance has fallen off a cliff in the last couple of processor generations
- All processor vendors are moving to multi-core designs
  - Even embedded processors
- But there are some major obstacles to adoption
  - Applications need to be explicitly concurrent
    - Automatic parallelization still not mainstream
  - (Correct) concurrent programming is difficult

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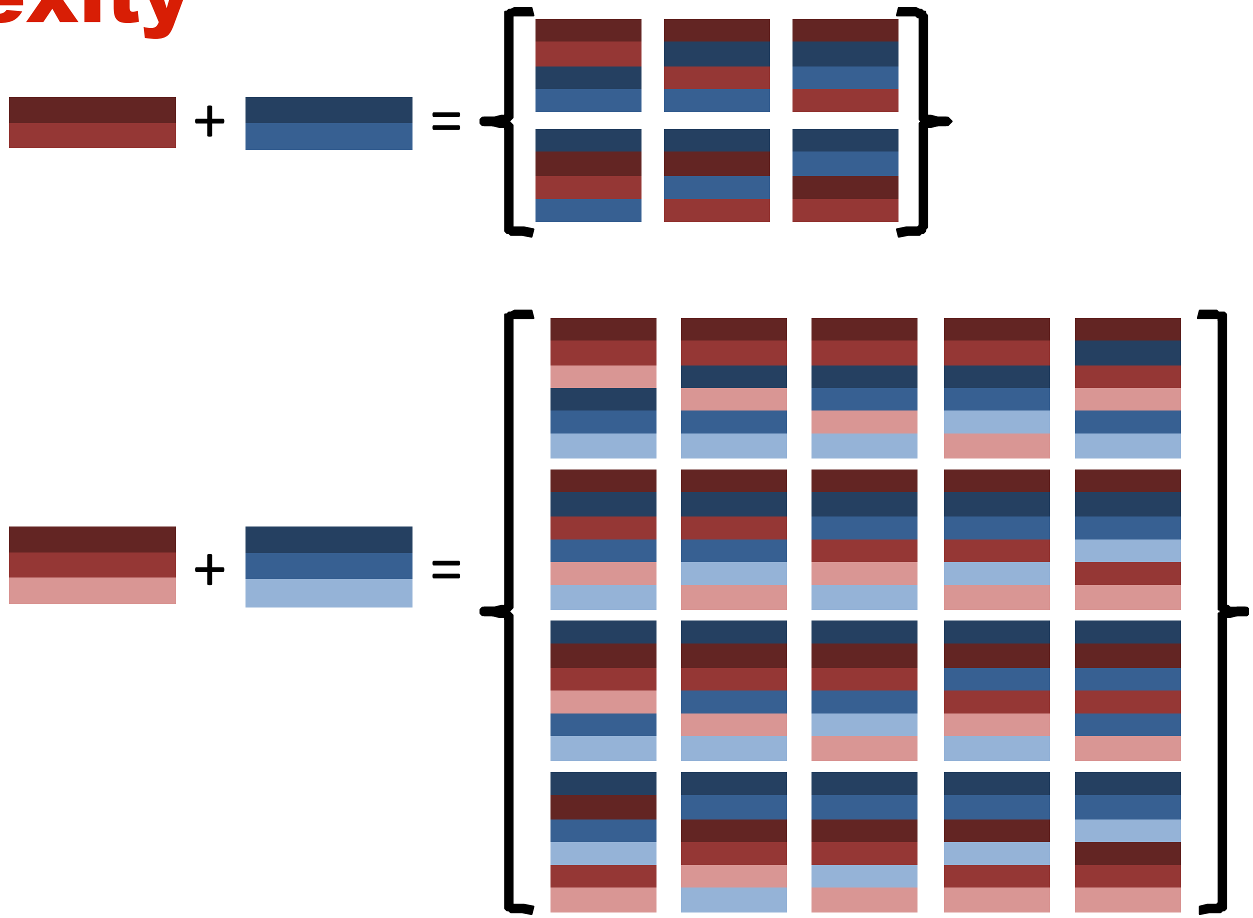
Concurrency Adds a New Source of Complexity



There are six possible interleavings of two threads with two instructions each. With three instructions each, there are twenty possible interleavings.

Non-deterministic Ordering in the Real World

- Real-world threads execute billions of instructions per second
- Interleavings are determined by real-world events and the system scheduler
- Ordering of events and scheduling choices are effectively non-deterministic
- Correctness of execution can depend on relative ordering
  - Race conditions are a major source of unintended time/scheduling dependence

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Eliminating Data Races

- Programs can be designed to be less sensitive to scheduling variation
  - Less sensitive => traditional software QA is more effective
- Potential data races and lock misuse are major sources of unintended sensitivity to scheduling variation
- CodeSonar helps eliminate potential data races and lock misuse

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Data Races

- A data race arises when:
  1. Multiple threads of execution access a shared piece of data
  2. At least one thread changes the value of the data
  3. Access is not separated by explicit synchronization
- Data races can leave a system in an inconsistent state
- Data races can lurk undetected and only show up in rare circumstances with mysterious symptoms

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Example Data Race

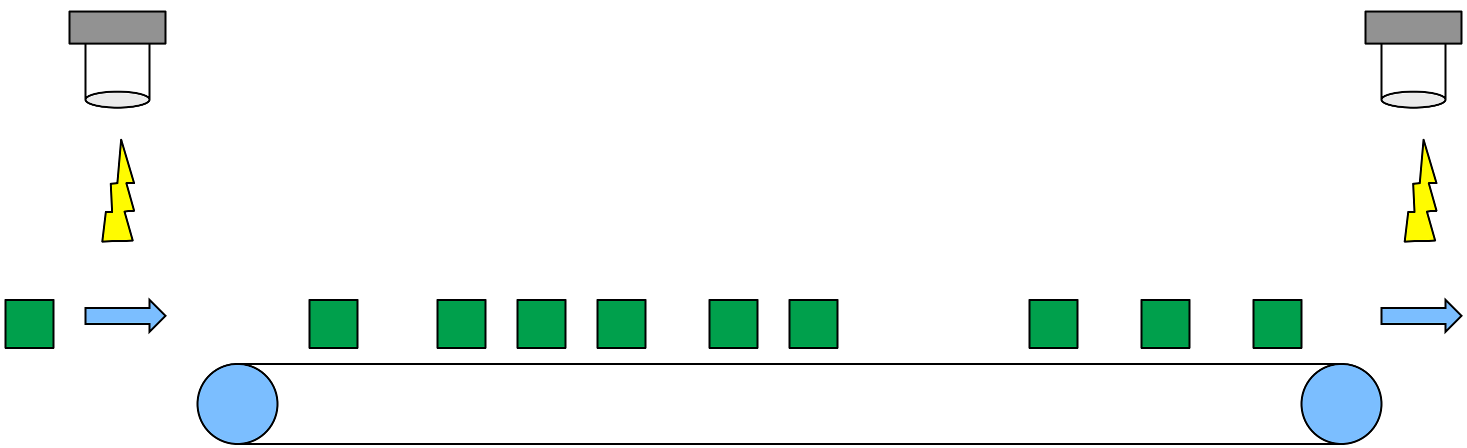
Thread 1

`count := count + 1;`

count: 10

Thread 2

`count := count - 1;`



`count := count + 1;`

load value from memory into register
increment value
store value back in memory

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Data Races are Hard to Debug

- Rare occurrence means little chance of detection during testing
- Diagnosis is difficult
- Reproducibility is a major problem
- Developers tend to assume each thread executes in-order (sequential consistency)
  - Effects of thread interaction easy to miss

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We Built Data Race Detection on an Existing Static Analysis Tool -- CodeSonar

- Static bug finder
- Uses symbolic execution for whole-program path-sensitive analysis
  - Bottom-up in the call graph (callees analyzed before callers)
  - Equivalent paths are summarized together to save space
  - Precise pointer analysis and feasible inter-procedural path extraction

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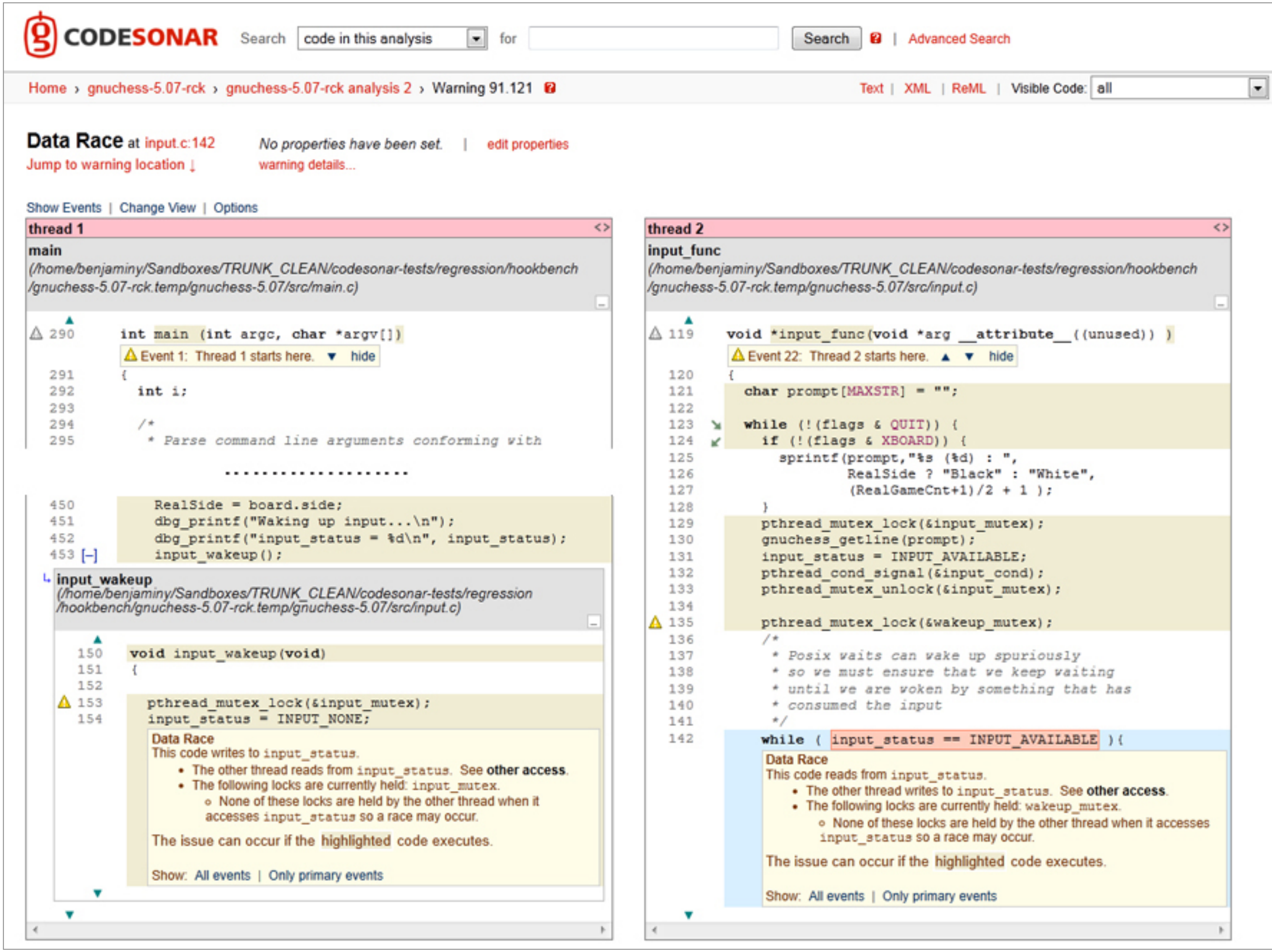
Finding Data Races at their Source

- We use a lockset-style approach
  - For each shared memory location, all accesses must be protected by a single lock
- During symbolic execution, find what locks are held when shared memory locations are accessed
- Find thread entry points (with library models)
- For each pair of thread entry points and each shared memory location, intersect the sets of locks to find possible data races


CODESONAR
Search code in this analysis for Search | Advanced Search
Home › gnuchess-5.07-rck › gnuchess-5.07-rck analysis 2 › Warning 91.121
Text | XML | ReML | Visible Code: all
Data Race at input.c:142
Jump to warning location ↓
No properties have been set. | edit properties
warning details...
Show Events | Change View | Options
thread 1
main
(/home/benjaminy/Sandboxes/TRUNK_CLEAN/codesonar-tests/regression/hookbench/gnuchess-5.07-rck.temp/gnuchess-5.07/src/main.c)
290 int main (int argc, char *argv[])
Event 1: Thread 1 starts here. hide
291 {
292 int i;
293
294 /*
295 * Parse command line arguments conforming with
450 RealSide = board.side;
451 dbg_printf("Waking up input...\n");
452 dbg_printf("input_status = %d\n", input_status);
453 [–] input_wakeup();
input_wakeup
(/home/benjaminy/Sandboxes/TRUNK_CLEAN/codesonar-tests/regression/hookbench/gnuchess-5.07-rck.temp/gnuchess-5.07/src/input.c)
150 void input_wakeup(void)
151 {
152
153 pthread_mutex_lock(&input_mutex);
154 input_status = INPUT_NONE;
Data Race
This code writes to input_status.
• The other thread reads from input_status. See other access.
• The following locks are currently held: input_mutex.
◦ None of these locks are held by the other thread when it accesses input_status so a race may occur.
The issue can occur if the highlighted code executes.
Show: All events | Only primary events
thread 2
input_func
(/home/benjaminy/Sandboxes/TRUNK_CLEAN/codesonar-tests/regression/hookbench/gnuchess-5.07-rck.temp/gnuchess-5.07/src/input.c)
119 void *input_func(void *arg __attribute__((unused)))
Event 22: Thread 2 starts here. hide
120 {
121 char prompt[MAXSTR] = "";
122
123 while (!(flags & QUIT)) {
124 if (!(flags & XBOARD)) {
125 sprintf(prompt,"%s (%d) : ",
126 RealSide ? "Black" : "White",
127 (RealGameCnt+1)/2 + 1);
128 }
129 pthread_mutex_lock(&input_mutex);
130 gnuchess_getline(prompt);
131 input_status = INPUT_AVAILABLE;
132 pthread_cond_signal(&input_cond);
133 pthread_mutex_unlock(&input_mutex);
134
135 pthread_mutex_lock(&wakeup_mutex);
136 /*
137 * Posix waits can wake up spuriously
138 * so we must ensure that we keep waiting
139 * until we are woken by something that has
140 * consumed the input
141 */
142 while (input_status == INPUT_AVAILABLE){
Data Race
This code reads from input_status.
• The other thread writes to input_status. See other access.
• The following locks are currently held: wakeup_mutex.
◦ None of these locks are held by the other thread when it accesses input_status so a race may occur.
The issue can occur if the highlighted code executes.
Show: All events | Only primary events

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No, that Data Race is Not Benign

- Double-checked locking for lazy initialization

- ```
  if (!init_flag) {
      lock();
      if (!init_flag) {
          my_data = ...;
          init_flag = true;
      }
      unlock();
  }
  tmp = my_data;
  ```

- See Boehm, "How to Miscompile Programs with 'Benign' Data Races"

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  ```

How CodeSonar Detects Deadlocks

- Most commonly adopted approach to avoiding deadlock is to assign a partial ordering to the resources
  - Proposed by Dijkstra in 1965 as a solution to the *Dijkstra/Hoare Dining Philosophers Problem*
- If it is possible for lock A to be held when lock B is acquired, A is “before” B
- CodeSonar examines the code and issues a *Conflicting Lock Order* warning if any pair of locks can be acquired in different orders by different threads

Additional Concurrency Checks

- *Process starvation*
- *Unknown Lock*
- *Missing Lock*, *Missing Unlock*, *Lock/Unlock Mismatch*
- *Double Lock*, *Double Unlock*
- *Try-lock that will never succeed*

Conclusions

- Multi-core processors are inevitable
  - Explicitly concurrent programming is the only reliable way to harness the performance of multi-cores today
- Concurrency errors are insidious
  - Difficult to reproduce, diagnose, and eliminate
  - Even apparently benign data races can have surprisingly detrimental consequences
- We are bringing research in static detection of concurrency defects to industrial-strength bug finding tools

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Thanks for Your Attention

Questions?

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