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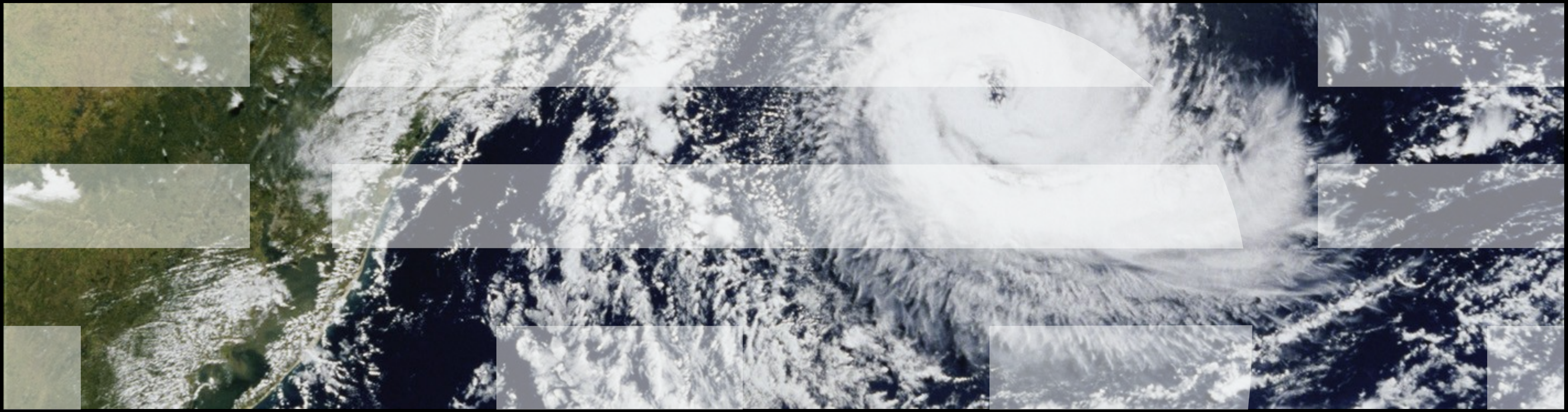
Advances in Validation of Concurrent Software



Overview

- Validation Trends Over Time
- Current Linux Kernel Validation Directions
- Future Validation Needs
- Validation Via Model Checking
- Multithreaded Model Checking

Validation Trends Over Time

Validation Trends Over Time

- Range of validation needed
- One-off hacked-up scripts have always been with us
  - Fix it if it fails, many bugs will go unnoticed and unexercised
- As have systems requiring extreme validation
  - Mission-critical business applications
    - Lose lots of money if it fails
  - High-volume consumer applications
    - Low-probability failures have a high probability of occurring
    - Another way to lose lots of money if it fails
  - Autonomous space-exploration systems
    - No way to fix it
  - Safety-critical embedded systems
    - Lose lives if it fails

Validation Trends Over Time: Paul's Journey

- 1975-6: Computer-dating program: < 5 users (data entry)
- 1977-1980: University housing system: 2 users
- 1981-1985: Building control system: ~100 users
  - Plus other embedded projects with similar user base
- 1986-1987: System administrator: ~50 users
- 1988-1990: Research prototypes: 1 user

Informal testing sufficed

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- 1988-1990: Research prototypes: 1 user
- 1990-2000: Sequent DYNIX/ptx: ~6,000 sites, mission critical

Formal unit and stress testing required: “tlbtest” rather than “rcutorture”, but...

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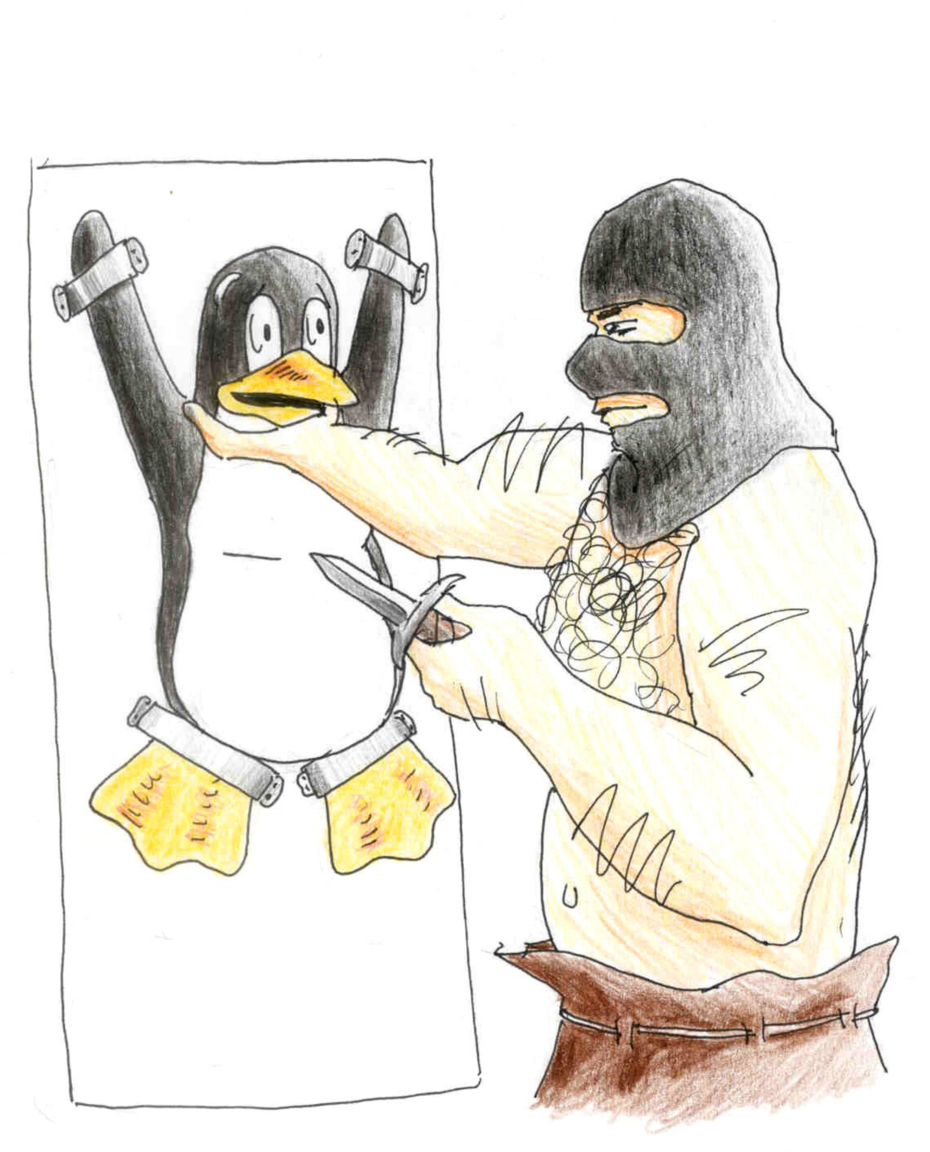
- 1988-1990: Research prototypes: 1 user
- 1990-2000: Sequent DYNIX/ptx: ~6,000 sites, mission critical
- **2001-present: Linux kernel: ~1M – ~1G OS instances**

What do we do now?

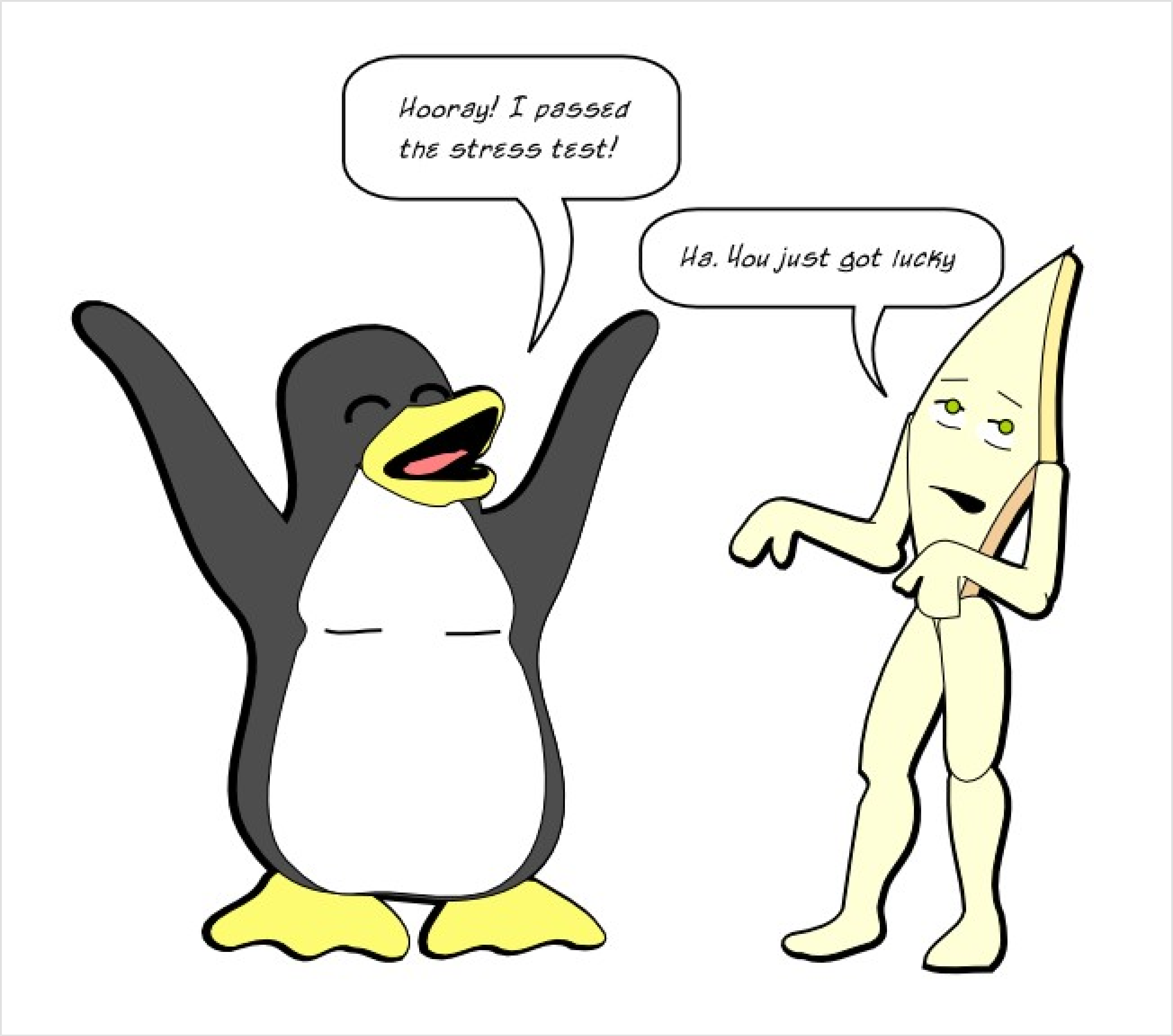
Validation: Paul's Philosophy

- Torture your code to the best of your ability, because otherwise it will torture you to the best of its ability!

Validation: Paul's Philosophy



Validation: Paul's Philosophy: Limits to Validity



http://paulmck.livejournal.com/36150.html

Validation: Paul's Philosophy

- Torture your code to the best of your ability, because otherwise it will torture you to the best of its ability!
- But with a billion running instances out there, it is really hard to torture your code more viciously than the real world is going to torture it

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- But with a billion running instances out there, it is really hard to torture your code more viciously than the real world is going to torture it
- And failing to torture your code more than the real world is going to torture it will result in bugs escaping into the wild

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- Some of which will result in security exploits

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- Torture your code to the best of your ability, because otherwise it will torture you to the best of its ability!
- But with a billion running instances out there, it is really hard to torture your code more viciously than the real world is going to torture it
- And failing to torture your code more than the real world is going to torture it will result in bugs escaping into the wild
- Some of which will result in security exploits
- On the other hand, the Linux kernel community has been doing some really cool validation work!

Current Linux Kernel Validation Directions

Current Linux Kernel Validation Directions

- Why are we getting reasonable reliability on 1G instances???
  - At >15M lines of code, there ***are*** bugs
  - Million-year bugs happen about ***three times per day***
  - And some bugs do get through

Current Linux Kernel Validation Directions

- Why are we getting reasonable reliability on 1G instances???
  - At >10M lines of code, there ***are*** bugs
  - Million-year bugs happen about ***three times per day***
  - And some bugs do get through
- The bulk of Linux's installed base has few CPUs
  - Many SMP bugs found and fixed on larger server systems
  - But the CPU counts of “small” embedded systems increasing
- The bulk of Linux's installed base has predictable workload
  - System testing can find most of the relevant bugs
  - But smartphones are becoming general-purpose systems, which will render system testing less effective
- Fortunately lots of validation: testing and tooling!!!

Linux Kernel Validation Overview

- Code review: 10,000 eyes
  - Not that review has kept pace with change rate and complexity
  - From v3.11 to v3.12:
    - 8636 files changed, 587981 insertions(+), 264385 deletions(-)
- Unit/Stress tests
  - rcutorture, locktest, kernbench, hackbench, ...
  - Linux Test Project, Dave Jones's Trinity (quite effective lately)
- Automated/recurring testing
  - Stephen Rothwell's -next testing
  - Fengguang Wu's kbuild test robot (see next slide)
  - Frequent testing from many individuals and organizations
- Tools: sparse, lockdep, coccinelle, smatch, ...
- A big “Thank You!!!” to everyone helping with this!!!

Fengguang Wu's kbuild test robot

```
tree:   git://git.kernel.org/pub/scm/linux/kernel/git/paulmck/linux-
rcu.git rcu/dev
head:   7f797be6ab3cfb47e34ffe44a1a8ee8d6728893a
commit: 7f797be6ab3cfb47e34ffe44a1a8ee8d6728893a [42/42] rcu:
Consistent rcu_is_watching() naming
config: x86_64-randconfig-a0-0914 (attached as .config)

All error/warnings:

   In file included from include/linux/srcu.h:33:0,
                    from include/linux/notifier.h:15,
                    from include/linux/memory_hotplug.h:6,
                    from include/linux/mmzone.h:797,
                    from include/linux/gfp.h:4,
                    from include/linux/slab.h:12,
                    from include/linux/crypto.h:24,
                    from arch/x86/kernel/asm-offsets.c:8:
   include/linux/rcupdate.h: In function 'rcu_read_lock_held':
>> include/linux/rcupdate.h:354:2: error: implicit declaration of
function 'rcu_is_watching' [-Werror=implicit-function-declaration]
```

Fengguang Wu's kbuild test robot

```
vim +/rcu_is_watching +354 include/linux/rcupdate.h

   348   * offline from RCU perspective, so check for those as well.
   349   */
   350  static inline int rcu_read_lock_held(void)
   351  {
   352          if (!debug_lockdep_rcu_enabled())
   353                  return 1;
 > 354          if (!rcu_is_watching())
   355                  return 0;
   356          if (!rcu_lockdep_current_cpu_online())
   357                  return 0;
```

Future Validation Needs

Future Validation Needs

- Typical CPU counts will continue increasing for some time
  - Including for the low-end embedded systems that make up the bulk of the Linux kernel's installed base
- Scalability needs will force more aggressive parallelism
  - lockdep can't help much with atomic operations and memory barriers!
  - Manual inspection does not scale with Linux's rate of development
  - Additional automated inspection will be needed
- Many other needs, including validation against standards
  - To say nothing of validation ***of*** standards...
- But this presentation will focus on concurrency

Future Validation Needs: RCU Anecdotes

- As with airplane safety, you need to look beyond bugs in use:
  - "Near misses" caught by distro testing
    - Recent day-1 RCU CPU stall warning bug (Michal Hocko &c)
    - Shortcoming in my development methods: I need to take diagnostic code more seriously
  - "Near misses" caught by mainline testing
    - Mid-2011 v3.0-rc7 RCU/interrupt/scheduler race
    - RCU is becoming more intertwined with the rest of the kernel: I need to work to increase the isolation between RCU and the rest of the kernel
  - "Near misses" caught by my testing
    - Late 2012 day-1 RCU initialization race
    - See next slide...
- That said, in RCU "day 1" is a slippery concept
  - Three categories of statements in RCU remain from v2.6.12

Late 2012 Day-1 RCU initialization Race

1. CPU 0 completes grace period, starts new one, cleaning up and initializing up through first leaf rcu_node structure
2. CPU 1 passes through quiescent state (new grace period!)
3. CPU 1 does rcu_read_lock() and acquires reference to A
4. CPU 16 exits dyntick-idle mode (back on ***old*** grace period)
5. CPU 16 removes A, passes it to call_rcu()
6. CPU 16 becomes associates callback with next grace period
7. CPU 0 completes cleanup/initialization of rcu_node structures
8. CPU 16 associates callback with now-current grace period
9. All remaining CPUs pass through quiescent states
10. Last CPU performs cleanup on all rcu_node structures
11. CPU 16 notices end of grace period, advances callback to “done” state
12. CPU 16 invkes callback, freeing A (too bad CPU 1 is still using it)

RCU reviewers are smart, but I cannot expect them to find this.

Validation Via Model Checking

Validation Via Model Checking

- Researchers' traditional focus:
  - Full validation of *all* behaviors of the system
    - Too bad that a description of all behaviors is as big as the system itself
  - Strong ordering (e.g., Promela/spin)
    - Too bad that all modern systems are weakly ordered, even x86
  - Special-purpose languages
    - Too bad that most parallel code is in general-purpose languages like C/C++
- Richard Bornat, 2011:
  - Our job is to validate the code developers write, in the environment they write it in, and in the language that they write it.
- A number of researchers have been taking this to heart
  - Peter Sewell, Susmit Sarkar, Jade Alglave, Daniel Kroening, Michael Tautschnig, Alexey Gotsman, Noam Riznetsky, Hongseok Yang, ...

Concurrency and Validation: Sewell & Sarkar's Group

- Formalization of weak-memory models (x86, Power, ARM)
  - http://lwn.net/Articles/470681/
- Tools for full state-space search of concurrent code

```
PPC IRIW.litmus
""
(* Traditional IRIW. *)
{
0:r1=1; 0:r2=x;
1:r1=1;         1:r4=y;
2:      2:r2=x; 2:r4=y;
3:      3:r2=x; 3:r4=y;
}
 P0           | P1           | P2                 | P3                 ;
 stw r1,0(r2) | stw r1,0(r4) | lwz r3,0(r2)       | lwz r3,0(r4)       ;
              |              | sync               | sync               ;
              |              | lwz r5,0(r4)       | lwz r5,0(r2)       ;

exists
(2:r3=1 /\ 2:r5=0 /\ 3:r3=1 /\ 3:r5=0)
```

Concurrency and Validation: Sewell & Sarkar's Group

- Extremely valuable tool
  - Definitive answers for atomic operations and memory barriers
  - Explores every state that a real system could possibly enter
  - Near production quality
- Some shortcomings:
  - Need to translate code to assembly language
  - Does not handle arbitrary loops or arrays
  - Only handles very small code sequences
  - Applies to Power, ARM, C/C++11, but not generic Linux barriers
  - ~14 CPU-hours and ~10GB to validate example, 3.3MB of output
    - Failures detected more quickly
    - Omitting sync instructions detects failure in less than three CPU minutes
    - And knowing in 14 hours is better than just not knowing!
- Important milestone in handling real-world parallelism

Validation Via Model Checking: Alglave, Kroening, and Tautschnig

- Programming languages might be Turing complete, but you can get a long way with finite state machines
  - Any real system is a finite state machine
- Finite state machines represented by logic expressions
  - Assertions can be tested with boolean satisfiabilty tester (SAT)
- SAT is NP complete
  - But full state-space searches are no picnic, either
  - And much progress on SAT: million-variable problems now feasible

Code To Logic Expression

```
CPU 0          CPU 1
x = 1;         r1 = x;
x = 2;
```

- Initial value of x is zero
- Assume cache coherence (stores of 1 and 2 are ordered)
- Introduce three auxiliary variables:
  - Ls1s2: Load happened before store of 1
  - s1Ls2: Load happened between store of 1 and store of 2
  - s1s2L: Load happened after store of 2
- Expression:
  - Ls1s2→r1==0 && s1Ls2→r1==1 && s1s2L→r1==2
- Convert implication to boolean operators:
  - (!Ls1s2 || r1==0) && (!s1Ls2 || r1==1) && (!s1s2L || r1==2)

Code To Logic Expression

```
CPU 0        CPU 1
x = 1;       r1 = x;
x = 2;
```

- Initial logic expression:
  - (!Ls1s2 || r1==0) && (!s1Ls2 || r1==1) && (!s1s2L || r1==2)
- Problem: What if all three of Ls1s2, s1Ls2, s1s2L are set?
  - This would mean that CPU 1's load is both before and after both stores!
  - Need some way to rule this out
  - (Ls1s2 && !s1Ls2 && !s1s2L) || (!Ls1s2 && s1Ls2 && !s1s2L) || (!Ls1s2 && !s1Ls2 && s1s2L)
- Combining these:
  - ((Ls1s2 && !s1Ls2 && !s1s2L) || (!Ls1s2 && s1Ls2 && !s1s2L) || (!Ls1s2 && !s1Ls2 && s1s2L)) && (!Ls1s2 || r1==0) && (!s1Ls2 || r1==1) && (!s1s2L || r1==2)

Code To Logic Expression

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CPU 0          CPU 1
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  - (!Ls1s2 || r1==0) && (!s1Ls2 || r1==1) && (!s1s2L || r1==2)
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- Combining these:
  - ((Ls1s2 && !s1Ls2 && !s1s2L) || (!Ls1s2 && s1Ls2 && !s1s2L) || (!Ls1s2 && !s1Ls2 && s1s2L)) && (!Ls1s2 || r1==0) && (!s1Ls2 || r1==1) && (!s1s2L || r1==2)
- And this is supposed to make things simpler???

Code To Logic Expression

```
CPU 0          CPU 1
x = 1;         r1 = x;
x = 2;
```

- “Full” logic expression:
  - ((Ls1s2 && !s1Ls2 && !s1s2L) || (!Ls1s2 && s1Ls2 && !s1s2L) || (!Ls1s2 && !s1Ls2 && s1s2L)) && (!Ls1s2 || r1==0) && (!s1Ls2 || r1==1) && (!s1s2L || r1==2)
  - In real life, need binary expansion of r1
  - And expressions to relate the values of x to each other
- There is a lot of software to analyze such expressions
  - And to simplify and manipulate them
  - And to generate them automatically from C code
  - Which is a good thing because doing it by hand would be a pain!
- In particular, there is a lot of code to determine what combinations of variables satisfies a given logic expression

C Bounded Model Checker (cbmc)

- Takes smallish C programs as input, converts to SSA
- Generates corresponding logic expressions
- Optionally takes limits on loop unrolling
  - Arbitrary loops are not handled
  - Something about them generating logic expressions of infinite size
- Evaluates array bounds and assertions, among other things
  - This presentation will focus on assertions
  - Big benefit: Developer specifies correctness criteria
- Does not handle multithreading
  - But you have to start somewhere...

Example #1 cbmc Verification: Input

```
#include <stdio.h>

int main(int argc, char *argv[])
{
        int i;

        if (argc < 2) {
                printf("Usage: %s n\n", argv[0]);
                return 1;
        }
        i = atoi(argv[1]);
        i = i * 2 + 1;
        assert(i & 0x1);
        return 0;
}
```

Example #1 cbmc Verification: Output

```
$ cbmc even.c
file even.c: Parsing
Converting
Type-checking even
file even.c line 11 function main: function `c::atoi' is not declared
Generating GOTO Program
Adding CPROVER library
Function Pointer Removal
Partial Inlining
Generic Property Instrumentation
Starting Bounded Model Checking
size of program expression: 29 assignments
simple slicing removed 3 assignments
Generated 1 VCC(s), 1 remaining after simplification
Passing problem to propositional reduction
Running propositional reduction
Solving with MiniSAT2 without simplifier
1476 variables, 4036 clauses
empty clause: negated claim is UNSATISFIABLE, i.e., holds
Runtime decision procedure: 0.017s
VERIFICATION SUCCESSFUL
```

Example #2 cbmc Verification: Input

```
#include <stdio.h>

int main(int argc, char *argv[])
{
        int i;

        if (argc < 2) {
                printf("Usage: %s n\n", argv[0]);
                return 1;
        }
        i = atoi(argv[1]);
        i = i * 2;
        assert(i & 0x1);
        return 0;
}
```

Example #2 cbmc Verification: Output

```
$ cbmc even-bad.c
. . .
State 22 file even-bad.c line 12 function main thread 0
----------------------------------------------------
  main::1::i=2 (00000000000000000000000000000010)

Violated property:
  file even-bad.c line 13 function main
  assertion
  (_Bool)(i & 1)

VERIFICATION FAILED
```

Example #3 cbmc Verification: Input

```
#include <stdio.h>

extern int nondet_int(void);

int main(int argc, char *argv[])
{
        int a, b, c;

        a = nondet_int();
        b = nondet_int();
        c = nondet_int();
        if (a <= 0 || a > 1023 || b <= 0 || b > 1023 || c <= 0 || c > 1023) {
                printf("Usage: %s a b c\n", argv[0]);
                printf("\tValue must be 0 < v <= 1023\n", argv[0]);
                return 2;
        }
        assert(a * a * a + b * b * b != c * c * c);
        return 0;
}
```

Example #3 cbmc Verification: Output

```
$ cbmc fermat.c
file fermat.c: Parsing
Converting
Type-checking fermat
Generating GOTO Program
Adding CPROVER library
Function Pointer Removal
Partial Inlining
Generic Property Instrumentation
Starting Bounded Model Checking
size of program expression: 37 assignments
simple slicing removed 1 assignments
Generated 1 VCC(s), 1 remaining after
simplification
Passing problem to propositional reduction
Running propositional reduction
Solving with MiniSAT2 without simplifier
24573 variables, 29508 clauses
SAT checker: negated claim is UNSATISFIABLE,
i.e., holds
Runtime decision procedure: 158.163s
VERIFICATION SUCCESSFUL
```

← **Why so slow?**

Exhaustive testing can be faster, but often more work

Example #3 cbmc Verification: Output

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$ cbmc fermat.c
file fermat.c: Parsing
Converting
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Runtime decision procedure: 158.163s
VERIFICATION SUCCESSFUL
```

Why so slow?
Multiplication!!!

Exhaustive testing can be faster, but often more work

C Bounded Model Checker (cbmc) Summary

- CMU research project
- Readily available open source: http://www.cprover.org/cbmc/
- Part of several Linux distros
- Handles C code
- Reasonably robust and documented
  - Theory of operation:http://www.cprover.org/cbmc/doc/cbmc-slides.pdf
  - Tutorial: http://www.cprover.org/cprover-manual/cbmc.shtml
- Does not handle general loops, but allows bounded unrolling
  - And checks to see if unrolling was sufficient
- Does not handle threading
  - Though some extensions have been prototyped

Multithreaded Model Checking

Multithreaded Model Checking

- Alglave, Kroening, and Tautschnig produced prototype system with goto-cc, goto-instrument, and satabs
  - I became aware of this work by accident while in Rome...
- Memory model captured as additional constraints
- Easily scripted:

```
#!/bin/sh
goto-cc -o $1.goto $1.c
goto-instrument --wmm power $1.goto $1_power.goto
nthreads=`grep __CPROVER_ASYNC_ $1.c | wc -l`
nthreads=`expr $nthreads + 1`
satabs --concurrency --full-inlining --max-threads $nthreads $1_power.goto
```

Multithreaded Model Checking: IRIW Example Input

```
int __unbuffered_cnt=0;
int __unbuffered_p0_EAX=0;
int __unbuffered_p0_EDX=0;
int __unbuffered_p1_EAX=0;
int __unbuffered_p1_EDX=0;
int x=0;
int y=0;

void * P2(void * arg) {
  x = 1;
  // Instrumentation for CPROVER
  asm("sync ");
  __unbuffered_cnt++;
}

void * P3(void * arg) {
  y = 1;
  // Instrumentation for CPROVER
  asm("sync ");
  __unbuffered_cnt++;
}
```

```
void * P0(void * arg) {
  __unbuffered_p0_EAX = x;
  asm("sync ");
  __unbuffered_p0_EDX = y;
  // Instrumentation for CPROVER
  asm("sync ");
  __unbuffered_cnt++;
}

void * P1(void * arg) {
  __unbuffered_p1_EAX = y;
  asm("sync ");
  __unbuffered_p1_EDX = x;
  // Instrumentation for CPROVER
  asm("sync ");
  __unbuffered_cnt++;
}
```

Multithreaded Model Checking: IRIW Example Input

```
int main() {
  __CPROVER_ASYNC_0: P0(0);
  __CPROVER_ASYNC_1: P1(0);
  __CPROVER_ASYNC_2: P2(0);
  __CPROVER_ASYNC_3: P3(0);
  __CPROVER_assume(__unbuffered_cnt==4);
  assert(__unbuffered_p0_EAX==0 || __unbuffered_p0_EDX == 1 ||
         __unbuffered_p1_EAX==0 || __unbuffered_p1_EDX == 1);
  return 0;
}
```

Multithreaded Model Checking: IRIW Example Output

```
. . .

Statistics of refiner:
Invalid states requiring more than 1 passive thread: 2
Spurious assignment transitions requiring more than 1 passive thread: 0
Spurious guard transitions requiring more than 1 passive thread: 0
Total transition refinements: 48
Transition refinement iterations: 10

VERIFICATION SUCCESSFUL
```

Same result as cppmem, but ***much*** faster: 2.61 CPU seconds vs ~14 CPU hours

Omitting sync instructions slows down to 134 CPU seconds: larger expressions

goto-cc/goto-instrument/satabs Summary

- Oxford research project
- Readily available open source: http://www.cprover.org/wmm/
- Download source and/or x86 binaries
- Handles C code, including some concurrency
- Early days: Robustness and documentation lacking
  - Number of threads specified in four different places, no diagnostics!
  - Working versions as follows:

```
$ sum goto-cc goto-instrument satabs
19375  4429 goto-cc
54447  5705 goto-instrument
24956  5969 satabs
```

- Does not handle general loops, but allows bounded unrolling
  - And checks to see if unrolling was sufficient

Validating Linux-Kernel RCU Implementation

Validating Linux-Kernel RCU Implementation

- I just happen to have some new RCU code...
  - “Is the whole system idle?” http://lwn.net/Articles/558284/
- So why not try goto-cc/goto-instrument/satabs?

Validating Linux-Kernel RCU Implementation

- I just happen to have some new RCU code...
  - “Is the whole system idle?” http://lwn.net/Articles/558284/
- So why not try goto-cc/goto-instrument/satabs?

```
Performing pointer analysis for concurrency-aware abstraction

satabs: value_set.cpp:1183: void value_sett::assign(const exprt&, const exprt&,
const namespacet&, bool): Assertion `base_type_eq(rhs.type(), type, ns)' failed.

Aborted (core dumped)
```

- Maybe 685 lines of code was too much...
  - Bug report in to authors

Validating Linux-Kernel RCU Implementation

- Another tool: impara
  - Very similar setup as goto-cc/goto-instrument/satabs
  - http://www.cprover.org/concurrent-impact/
- Doesn't deal nicely with dynamic memory allocation
  - Bug fix for this in the works

Validating Linux-Kernel RCU Implementation

- Another tool: impara
  - Very similar setup as goto-cc/goto-instrument/satabs
  - http://www.cprover.org/concurrent-impact/
- Doesn't deal nicely with dynamic memory allocation
  - Bug fix for this in the works
- So eliminate boot-time allocation in favor of static allocation

terminate called after throwing an instance of 'char const*'

- Bug report in to authors
  - Perhaps time to fall back to Promela and spin...
  - (In addition to pre-existing stress tests and review.)
  - But tools that take C code as input are much more convenient!!!

Summary

Summary

- Validation of the Linux kernel increasingly challenging
  - More code to validate
  - More instances to exercise obscure bugs
  - More CPUs, memory, and other invitations to rare bugs
- Linux kernel community has risen to the challenge
  - Review, aggressive testing, tooling
- Future requirements likely to be more severe
  - Full state-space modeling might be one way forward for concurrency
  - cppmem: slow and low-level but accurate and trustworthy
  - goto-cc/goto-instrument/satabs: fast and high-level, but early days
    - Will likely be able to handle larger problems

Summary

- Validation of the Linux kernel increasingly challenging
  - More code to validate
  - More instances to exercise obscure bugs
  - More CPUs, memory, and other invitations to rare bugs
- Linux kernel community has risen to the challenge
  - Review, aggressive testing, tooling
- Future requirements likely to be more severe
  - Full state-space modeling might be one way forward for concurrency
  - cppmem: slow and low-level but accurate and trustworthy
  - goto-cc/goto-instrument/satabs: fast and high-level, but early days
    - Will likely be able to handle larger problems: Eventually...
    - Ditto for impara

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Questions?