Using System-Specific Compiler Extensions to Find Errors in Systems Code

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Checking systems software

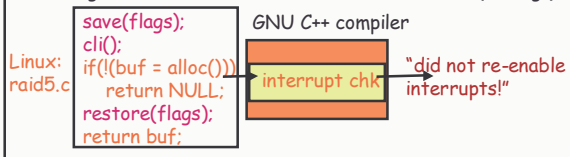
- Systems software has many ad-hoc restrictions:
  - "acquire lock L before accessing shared variable X"
  - "do not allocate large variables on 6K kernel stack"
- Error = crashed system. How to find errors?
  - Formal verification
    - + rigorous
    - - costly + expensive. *Very* rare to do for software
  - Testing:
    - + simple, few false positives
    - - requires running code: doesn't scale & can be impractical
  - Manual inspection
    - + flexible
    - - erratic & doesn't scale well.
  - What to do??

Another approach

- Observation: rules can be checked with a compiler
  - scan source for "relevant" acts check if they make sense
  - E.g., to check "disabled interrupts must be re-enabled:" scan for calls to disable()/enable(), check that they match, not done twice
- Main problem:
  - compiler has machinery to automatically check, but not knowledge
  - implementor has knowledge but not machinery
- Meta-level compilation (MC):
  - give implementors a framework to add easily-written, system-specific compiler extensions

Meta-level compilation (MC)

- Implementation:
  - Extensions dynamically linked into GNU g++ compiler
  - Applied down all paths in input program source
  - E.g. 64-line extension to check disable/disable (82 bugs)

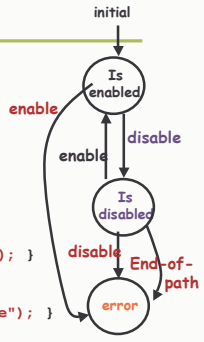


- Static detection of real errors in real systems:
  - 600+ bugs in Linux, OpenBSD, FLASH, Xok exokernel
  - most extensions < 100 lines, written by system outsiders

A bit more detail

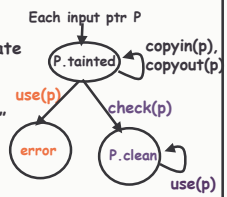
```
{ #include "linux-includes.h" }
sm chk_interrupts {
 decl { unsigned } flags;
 // named patterns
 pat enable = { sti(); }
       | { restore_flags(flags); };
 pat disable = { cli(); };

 // states
 is_enabled: disable ==> is_disabled
   | enable ==> { err("double enable"); }
   ;
 is_disabled: enable ==> is_enabled
   | disable ==> { err("double disable"); }
   | $end_of_path$ ==>
    { err("exiting w/intr disabled!"); }
   ; }
```



"X before Y" rule: system call pointers

- Applications are evil
  - OS much check all input pointers before use
  - one missing check = security hole
- MC checker:
  - Bind syscall ptr's to "tainted" state
  - tainted vars only touched w/ "safe" routines
  - or: explicit check to make "clean"




```
/* from sys/kern/disk.c */
int sys_disk_request(…
  struct buf *reqbp, u_int k) {
  ...
  /* bypass for direct scsi commands */
  if (reqbp->b_flags & B_SCSICMD)
      return sys_disk_scsicmd (sn, k, reqbp);
```

Deriving specification from common usage

- Problem: difficult to specify all user pointers
  - so:see what code usually does, deviations probably errors
  - if ever pass ptr to paranoid routine, make sure always do
- Found 5 security errors in Linux.
  - Canonical example: hole in an "ioctl" routine for some obscure device driver.

```
/* drivers/usb/evdev.c */
static int evdev_ioctl(..., unsigned long arg) {
    ...
    switch (cmd) {
      case EVIOCGVERSION:
         return put_user(EV_VERSION, (__u32 *) arg);
      case EVIOCGID: /* copy_to_user(to, from)! */
         return copy_to_user(&dev->id, (void *) arg,
                             sizeof(struct input_id));
```

Kernel alloc/dealloc rules

- Must check that alloc succeeded
- Must allocate enough space
- Must not use after free()
- Must free alloc'd object on error:

```
/* from drivers/char/tea6300.c */
client = kmalloc(sizeof *client,GFP_KERNEL);
if (!client)
      return -ENOMEM;
...
tea = kmalloc (sizeof *tea, GFP_KERNEL);
if (!tea)
      return -ENOMEM;
...
MOD_INC_USE_COUNT; /* bonus bug: kmalloc could sleep *
```

Stripped-down kernel malloc/free checker

```
decl { scalar } sz;          // match any scalar
decl { const int } retv;     // match const ints
state decl { any_ptr } v;    // match any pointer, can bind to a state

// Bind malloc results to "unknown" until observed
start:  { v = (any)malloc(sz) } ==> v.unknown
        | { free(v) } ==> v.freed;
// can compare in states unknown, null, not_null
v.unknown, v.null, v.not_null:
        { (v == 0) } ==>  true = v.null, false = v.not_null
        | { (v != 0) } ==>  true = v.not_null, false = v.null;
// Cannot reach error path with unknown or not-null
v.unknown, v.not_null:  { return retv; } ==>
        { if(mgk_int_cst(retv) < 0)  err("Error path leak!"); };
// No dereferences of null, freed, or unknown ptrs.
v.null, v.freed v.unknown:
        { *(any *)v } ==>  { err("Using ptr illegally!"); };
```

Some amusing bugs

- No check (130 errors, 11 false pos). Worse case (many uses):

```
/* include/linux/coda_linux.h:CODA_ALLOC */
ptr = (cast)vmalloc((unsigned long) size);
...
if (ptr == 0) printk("kernel malloc returns 0\n");
memset( ptr, 0, size );
```

- use after free (14 errors, 3 false pos): 5 cut&paste of

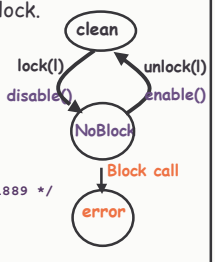
```
/* drivers/isdn/pcbit:pcbit_init_dev */
kfree(dev);
iounmap((unsigned char*)dev->sh_mem);
release_mem_region(dev->ph_mem, 4096);
```

- wrong size (2 errors)

```
/* drivers/parport/daisy.c:add_dev:50 */
newdev = kmalloc (GFP_KERNEL,sizeof(struct daisydev));
```

"In context Y, don't do X": blocking

- Linux: if interrupts are disabled, or spin lock held, do not call an operation that could block.
- MC checker:
  - Compute transitive closure of all potentially blocking fn's
  - Hit disable/lock: warn of any calls
  - 123 errors, 8 false pos




```
/* drivers/net/pcmcia/wavelan_cs.c */
spin_lock_irqsave (&lp->lock, flags); /* 1889 */
switch(cmd)
...
   case SIOCGIWPRIV:
      ...
      if(copy_to_user(wrq->u.data.pointer, ...))  /* 2305 */
            ret = -EFAULT;
```

Example: statically checking assert

- Assert(x) used to check "x" at runtime. Abort if false
  - compiler oblivious, so cannot analyze statically
  - Use MC to build an assert-aware extension

- Result: found 5 errors in FLASH.
  - Common: code cut&paste from other context
  - Manual detection questionable: 300-line path explosion between violation and check

General method to push dynamic checks to static

Result overview

Check	Errors	False pos	LOC
Static assert	5	0	100
Stack check	10+	0	53
Allocation	184	64	60
Blocking	123	8	131
Module race	~75	2	133
Mutex	82	201	64
FLASH	34	69	553
Total(+others)	~545	~226	~1100

Conclusions

- MC goal: make programming much more powerful
  - How: Raise compilation from level of programming language to the "meta level" of the systems implemented in that language
- MC works well in real, heavily tested systems
  - We found bugs in every system we've looked at.
  - Over 600 bugs in total, many capable of crashing system
  - Easily written by people unfamiliar w/ checked system

Currently:

- making correctors, using domain-knowledge to extract verifiable specs, deriving errors by usage deviations, performing meta-level optimization…

Conclusions

- Meta-level compilation:
  - Make compilers aggressively system-specific
  - Easy: digest sentence fragment, write checker/optimizer.
  - Result: Static, precise, immediate error diagnosis
  - As outsiders found errors in every system looked at
  - Over 600 bugs, many capable of crashing system

Currently:

- making correctors, using domain-knowledge to extract verifiable specs, deriving errors by usage deviations, performing meta-level optimization…

Bugs as deviant behavior

- One way to find bugs:
  - have a deep understanding of code semantics, detect when code makes no sense. Hard.
- Easier:
  - see what code usually does: deviations probably bugs
  - x protected by lock(a) 1000 times, by lock(b) once, probably an error

```
lock(a);   lock(a);   lock(a);   lock(a);   lock(b);   lock(a);
x++;       x++;       x++;       x++;       x++;       x++;
unlock(a); unlock(a); unlock(a); unlock(a); unlock(b); unlock(a);
```

- Find inverses by looking for common pairings
- More general: derive temporal orderings. Use machine learning to derive more sophisticated patterns?

What to do when static analysis too weak?

- Static analysis works in some cases, not well in others
  - hit undecidable problems with loop termination conditions, data values, pointers,…
- Alternative:
  - use domain-specific slicing to extract spec from code
  - run through verifier
- Main lever: a little domain knowledge goes a long way
  - e.g., strip out Linux TCP finite-state-machine by keying off of variable "sk->state"
  - Real example: checking FLASH code

Extracting specs from FLASH code

- Embedded sw for cache coherence in FLASH machine
  - errors crash or deadlock machine: can take week to track
  - typical protocol: 18K lines of hairy C code
- Extract specifications from source by simple slicing
  - found 9 errors in code
  - despite 5+ years of heavy testing and formal verification!
- How?
  - Given list of data structure fields and message operations, slice out all relevant operations
  - Compose with specification (manual) boilerplate
  - run through Murphi model checker
  - Levers: aliasing and globals, but in a stylized way that we can mostly ignore. 4 loops in code.

FLASH vs Murphi

FLASH

```
HANDLER_GLOBALS(header.nh.len) = LEN_CACHELINE;
if (! HANDLER_GLOBALS(h.hl.Pending)) {
    if (! HANDLER_GLOBALS(h.hl.Dirty)) {
        ASSERT(!HANDLER_GLOBALS(h.hl.IO));
        PI_SEND(F_DATA, F_FREE, F_SWAP,…,…);
        HANDLER_GLOBALS(h.hl.Local) = 1;
        /* ... deleted 14 lines */
    } else {
        ASSERT(!HANDLER_GLOBALS(h.hl.List));
        ASSERT(!HANDLER_GLOBALS(h.hl.RealPtrs));
```

Murphi

```
nh.len := len_cacheline;
if ((DH.Pending = 0)) then
    if ((DH.Dirty = 0)) then
      assert(nh.len != len_nodata);
      mbResult := pi_send_func(src, PI_Putt);
      DH.Local := 1;
    else
      assert((DH.List = 0));
      assert((DH.RealPtrs = 0));
```

Checkers into Correctors

- Problem: big system, lots of bugs
  - may not be your system or take too long to fix manually
- Can turn some classes of checkers into correctors:
  - "Do not allocate large variables on kernel stack": if you hit a violation, rewrite code to dynamically allocate var
  - "Do not call blocking memory allocator with interrupts disabled": hoist allocation out

```
cli();                          tmp = malloc(sizeof *p);
p = malloc(sizeof *p);   ⟶      cli();
sti();                          p = tmp;
                                sti();
```

  - "On error paths, rollback side-effects": dynamically track what these are, and reverse.
- Interesting: trade dynamic checks for simplicity

MC optimization

- Optimization rules similar to checking:
  - "if data is not shared with interrupt handlers, protect using spin locks rather than interrupt disable/enable
  - "to save an instruction when setting a message opcode, xor it with the new and old (msg.opcode ^= (new ^ old));
  - "replace quicksort with radix sort when sorting integers"
- Common rule: "In situation X, do Y rather than Z":
  - "if a variable is not modified, protect using read locks"

```
lock(q->lock);              read_lock(q->lock);
head = q->head;      ⟶     head = q->head;
n = q->nelem;               n = q->nelem;
unlock(q->lock);            read_unlock(q->lock);
```

  - and with a few lines: change opt into checker:

```
read_lock(q->lock);   ⟶   "modifying q with read lock!"
q->head = h;
```

MC analysis vs. traditional compiler analysis

- Meaning more apparent + domain-specific knowlege

```
Bigint a, b, c;
set(a, 3);
mul(b, a, a);          ⟶   printf("81");
mul(c, b, b);
printf("%s", bigint_to_str(c));
```

- Easier to bound side-effects: use knowledge of abstract state to ignore many concrete actions
- Aliasing less of a problem
  - typical: opaque handles vs normal mess of pointers
- Operations more coarse grain
  - read()/write() vs load/store; matrix ops vs +/-