Paul E. McKenney, IBM Distinguished Engineer, Linux Technology Center

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Validating Core Parallel Software

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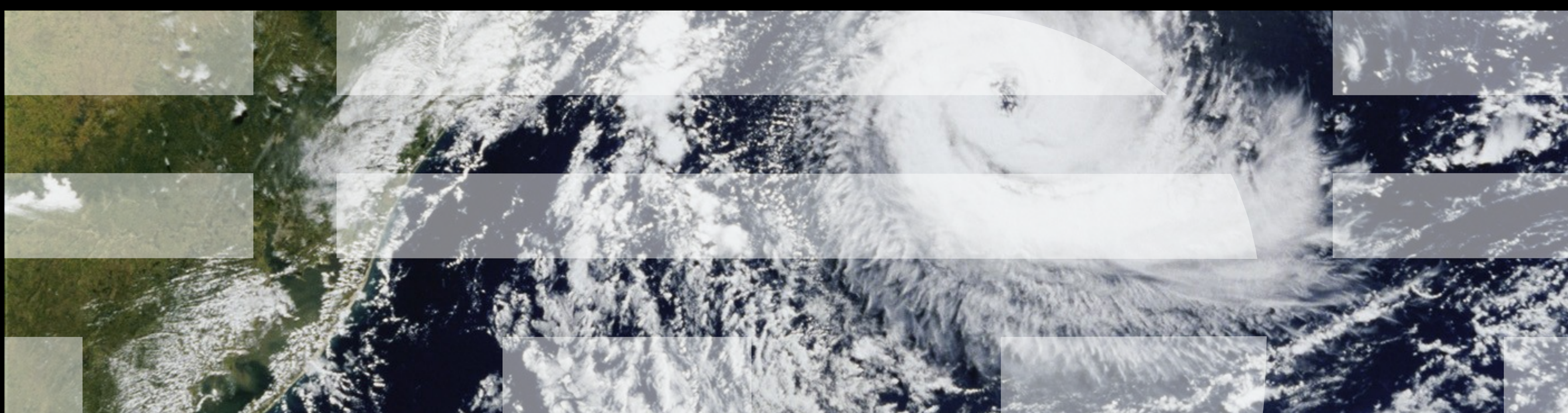

Overview

- Avoiding Bugs The Open-Source Way
- Avoiding Bugs By Design
- Avoiding Bugs By Process
- Avoiding Bugs By Mechanical Proofs
- Avoiding Bugs By Statistical Analysis
- Coping With Schedule Pressure
- But I Did All This And There Are Still Bugs!!!
- Summary and Conclusions

But First, Some Limitations...

- The only bug-free program is a trivial program
- A reliable programs has no known bugs

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- Fortunately... Unfortunately...

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- The Linux kernel is a non-trivial program
- In this imperfect real world, validation is more about reliability than about complete freedom from bugs

Avoiding Bugs The Open-Source Way

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- To 10,000 eyes, all bugs are shallow
  - But how many of those eyes are going to actually look at your patch?
  - When will they look at it?
  - How many will be experienced/clever enough to find your bugs?
- Many people test the Linux kernel
  - Some test random patches (perhaps even yours)
  - Some test -next
  - Some test maintainer trees
  - Some test mainline
  - Some test distro kernels
  - Will they run the HW/SW config and workload that will find your bug?
- Open source review/testing is wonderful, but for core parallel software you might want to be more proactive...

Avoiding Bugs By Design

Avoiding Bugs By Design

- Understand the Hardware
- Understand the Software Environment

Performance is a Key Correctness Criterion for Parallel Software

If you don't care about performance,
why on earth are you bothering with parallelism???

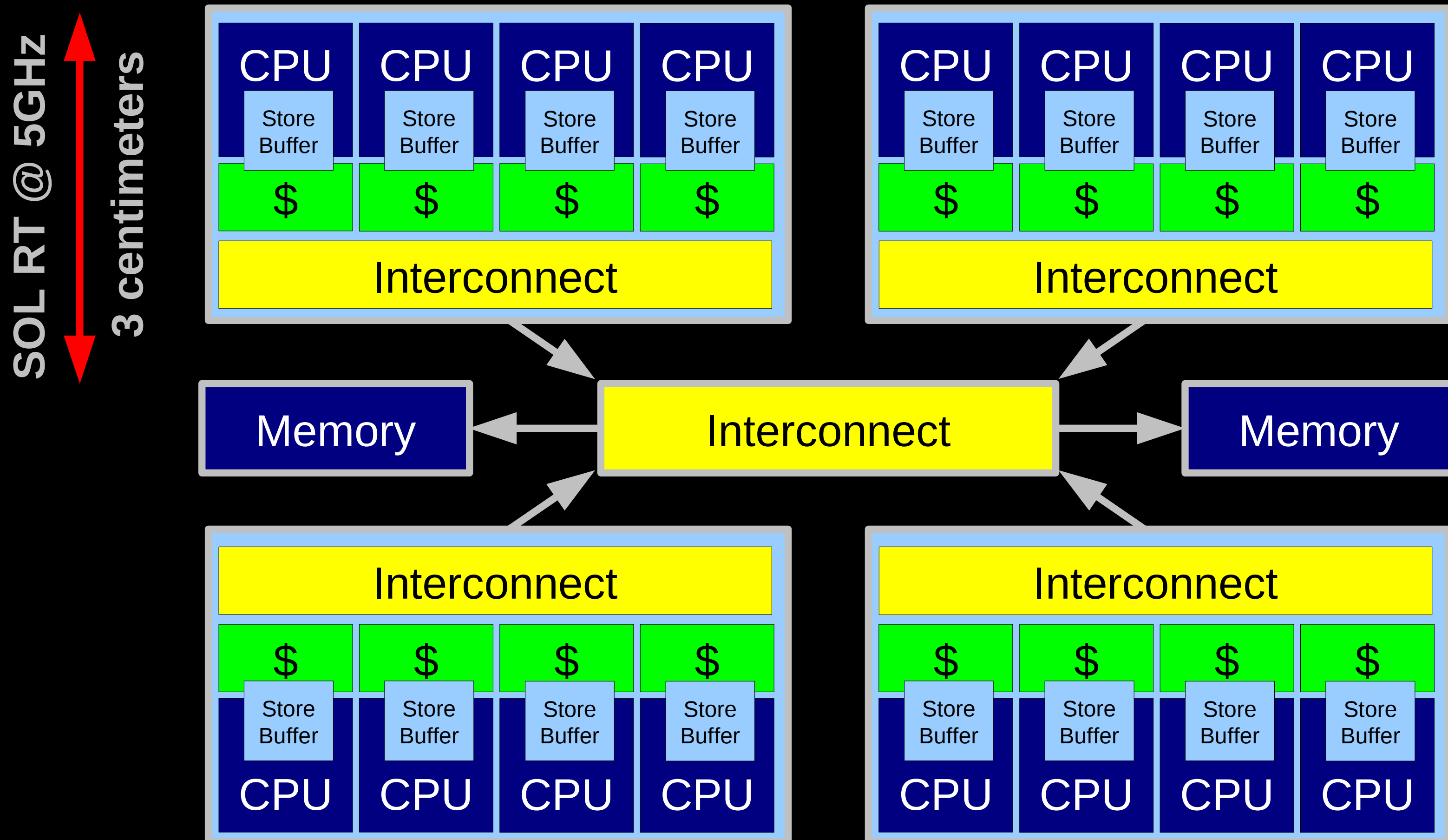
Performance of Synchronization Mechanisms

16-CPU 2.8GHz Intel X5550 (Nehalem) System

Operation	Cost (ns)	Ratio
Clock period	0.4	1
"Best-case" CAS	12.2	33.8
Best-case lock	25.6	71.2
Single cache miss	12.9	35.8
CAS cache miss	7.0	19.4
Single cache miss (off-core)	31.2	86.6
CAS cache miss (off-core)	31.2	86.5
Single cache miss (off-socket)	92.4	256.7
CAS cache miss (off-socket)	95.9	266.4

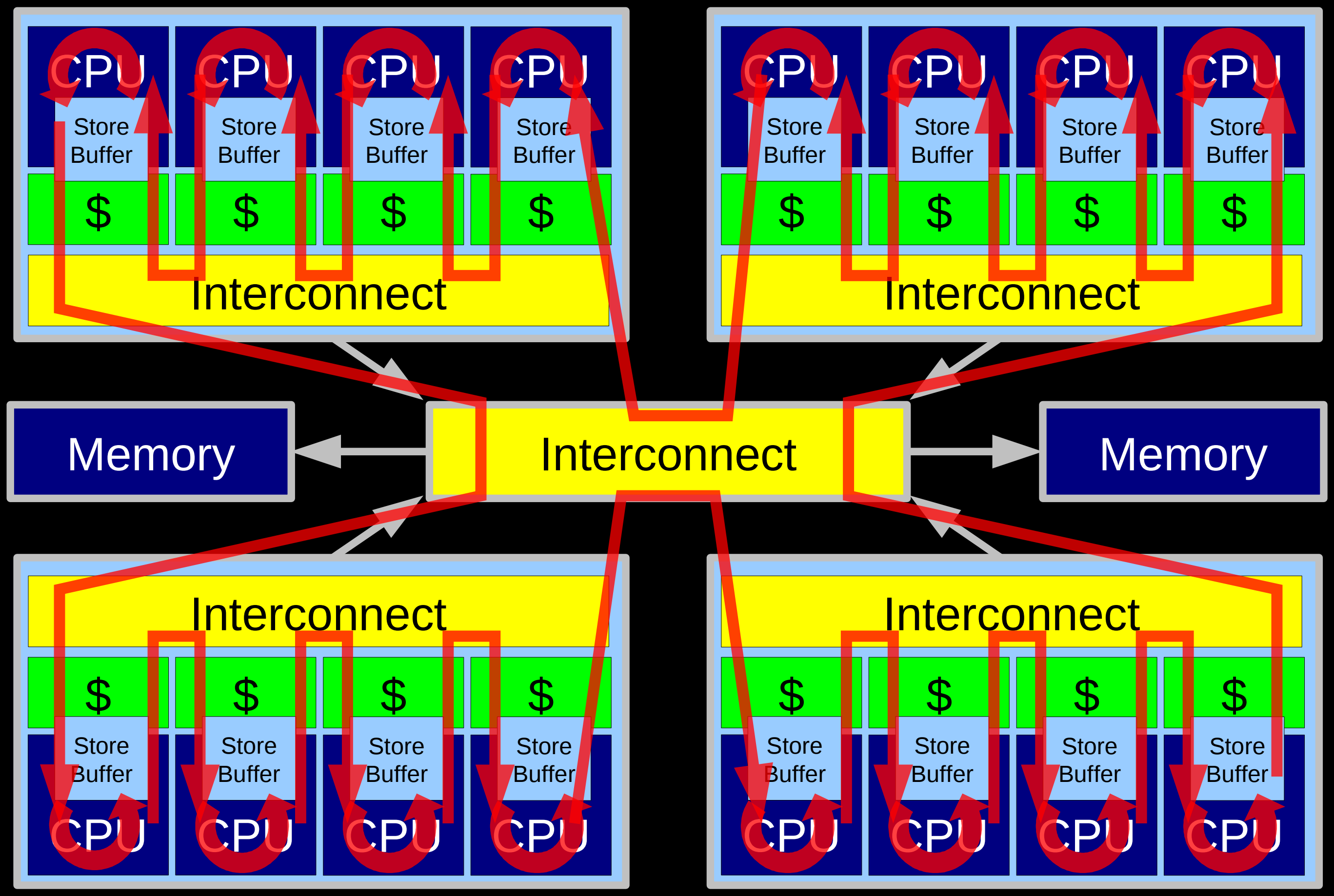
And these are best-case values!!! (Why?)

System Hardware Structure



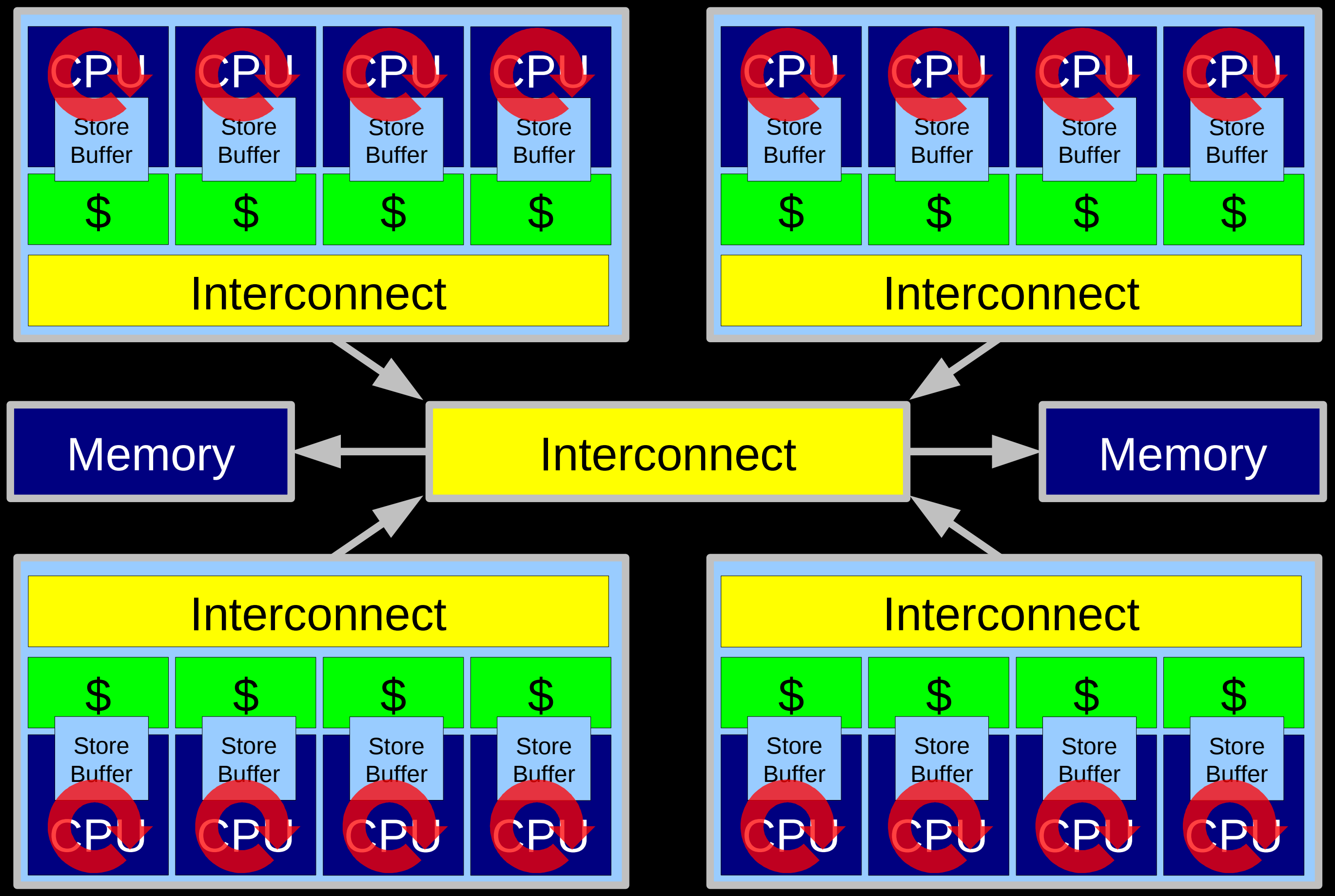
Electrons move at 0.03C to 0.3C in transistors and, so lots of waiting. 3D???

Atomic Instruction on Global Variable



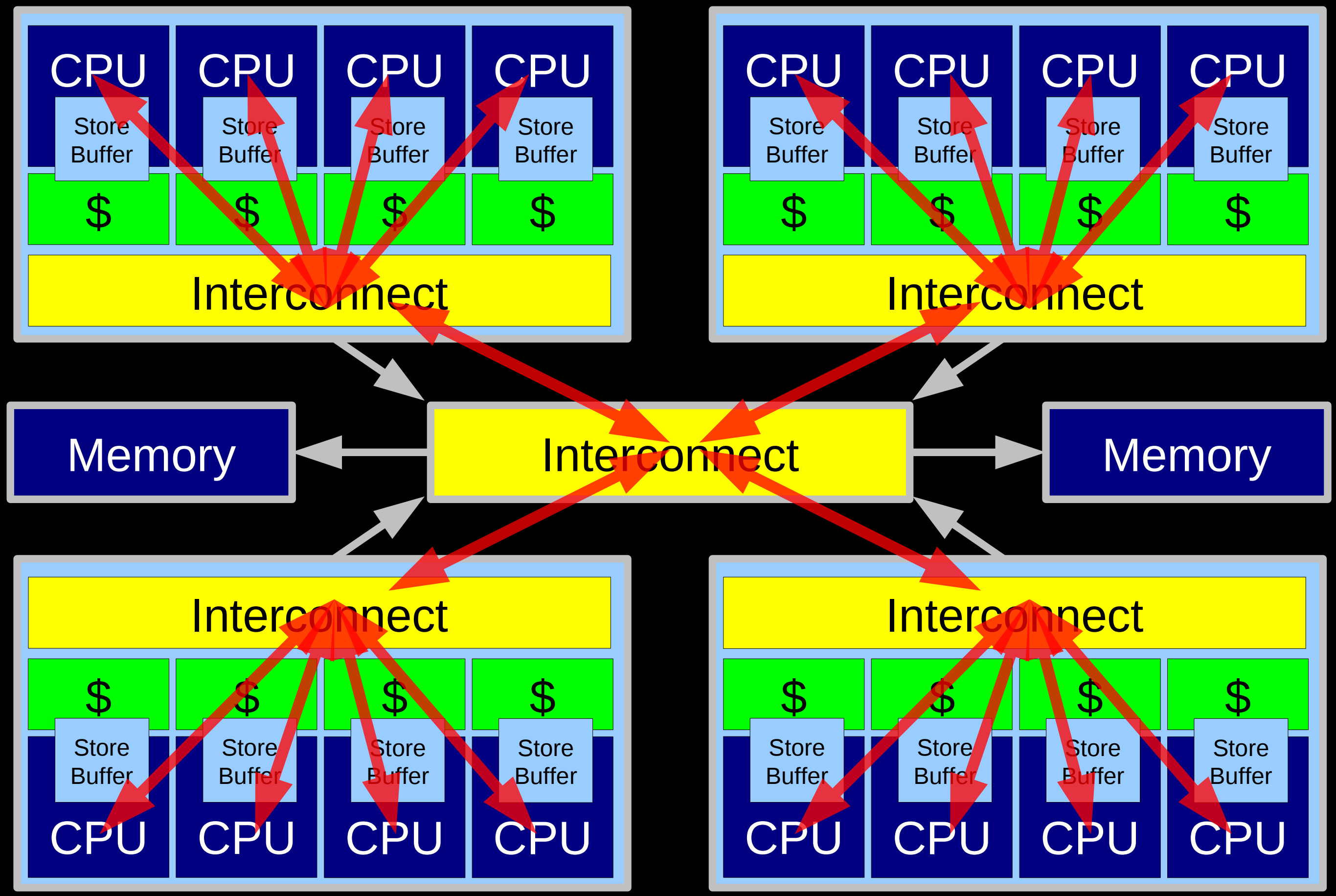
Lots and Lots of Latency!!!

Atomic Instruction on Per-CPU Variable



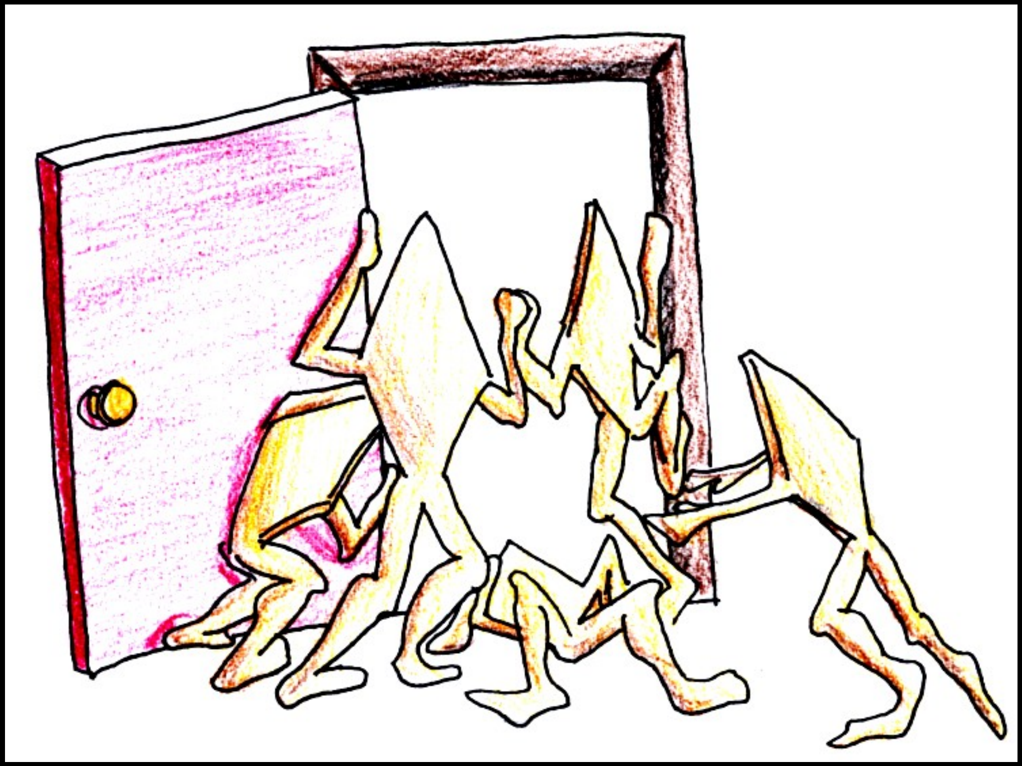
Little Latency, Lots of Instructions at Core Clock Rate

HW-Assist Atomic Increment of Global Variable



SGI systems used this approach in the 1990s, expect modern micros to pick it up.
Yes, HW changes. SW must change with it.

Design Principle: Avoid Bottlenecks



Only one of something: bad for performance and scalability.
Also typically results in high complexity.

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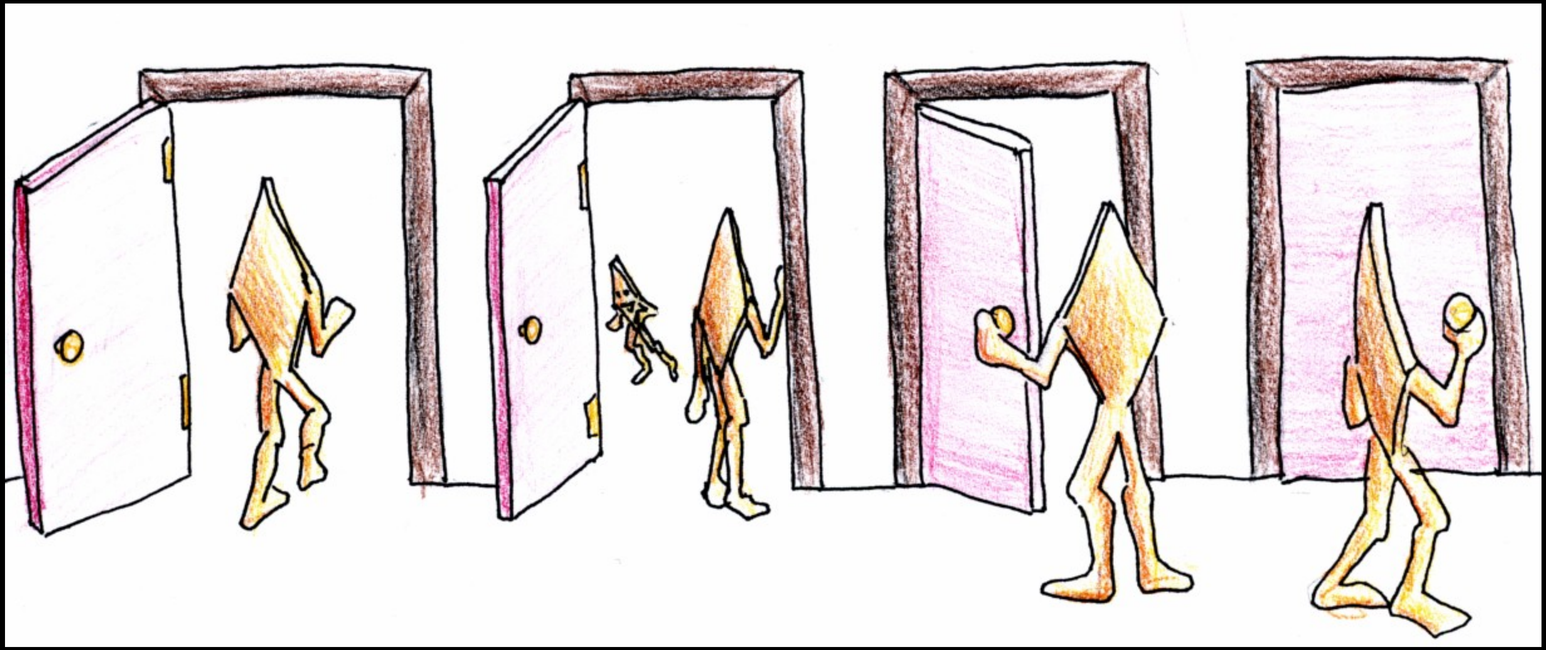
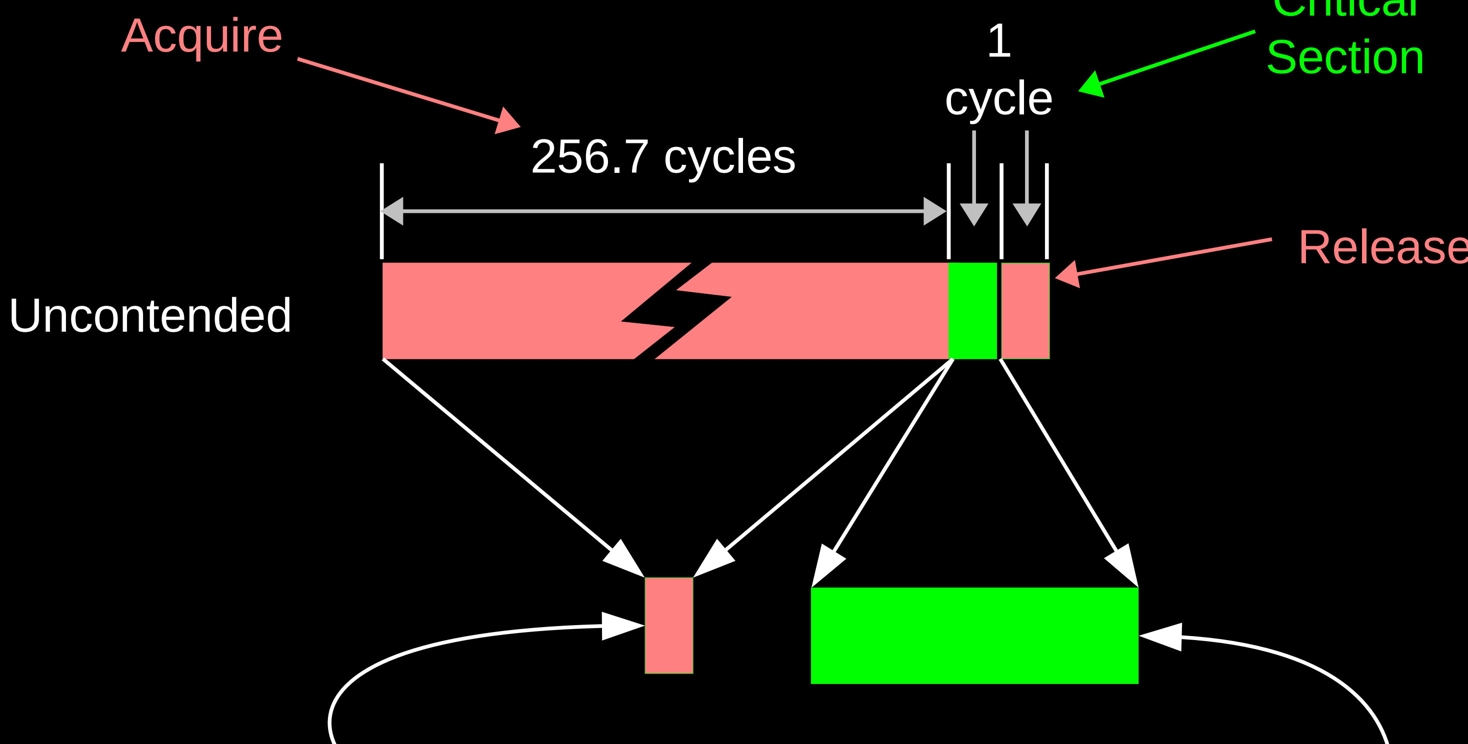


Many instances of something good!
Avoiding tightly coupled interactions is an excellent way to avoid bugs.

Design Principles: (1) “Cheap and Cheerful” and (2) “Get Your Money's Worth”

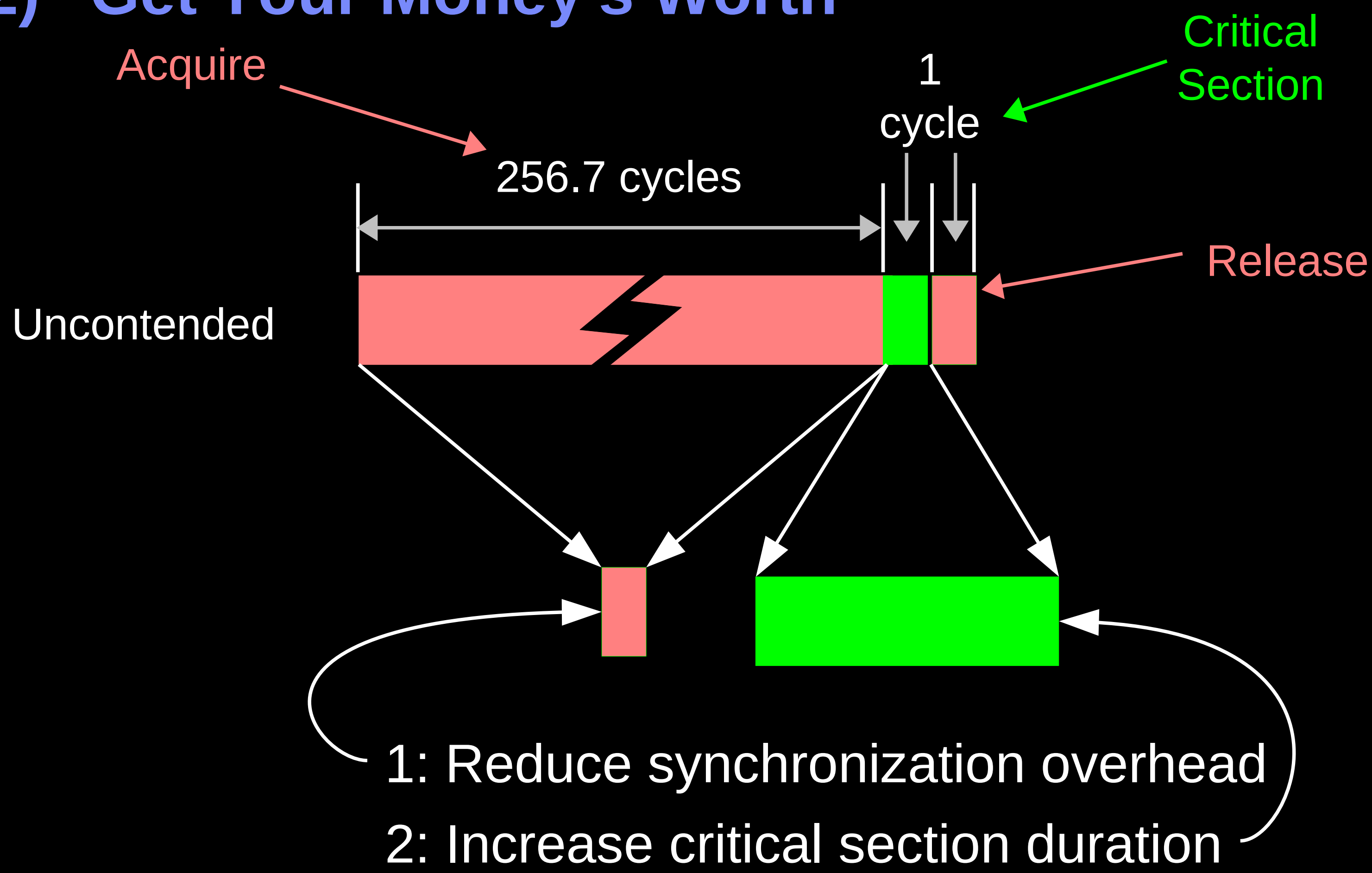


1: Reduce synchronization overhead

2: Increase critical section duration

Important safety tip:

Design Principles: (1) “Cheap and Cheerful” and (2) “Get Your Money's Worth”



1: Reduce synchronization overhead

2: Increase critical section duration

Important safety tip: You need both.

Understand the Hardware: Summary

- A strong understanding of the hardware helps rule out infeasible designs early in process
- Understanding hardware trends helps reduce the amount of future rework required
- Ditto for low-level software that your code depends on
  - In my case, things like in_irq() and user-mode helpers...
- Of course both the hardware and low-level software will change with time...
  - Even if it is now correct, your code will eventually be wrong...

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  - Even if it is now correct, your code will eventually be wrong...
  - This is one reason why we do regression testing

Understand the Software Environment

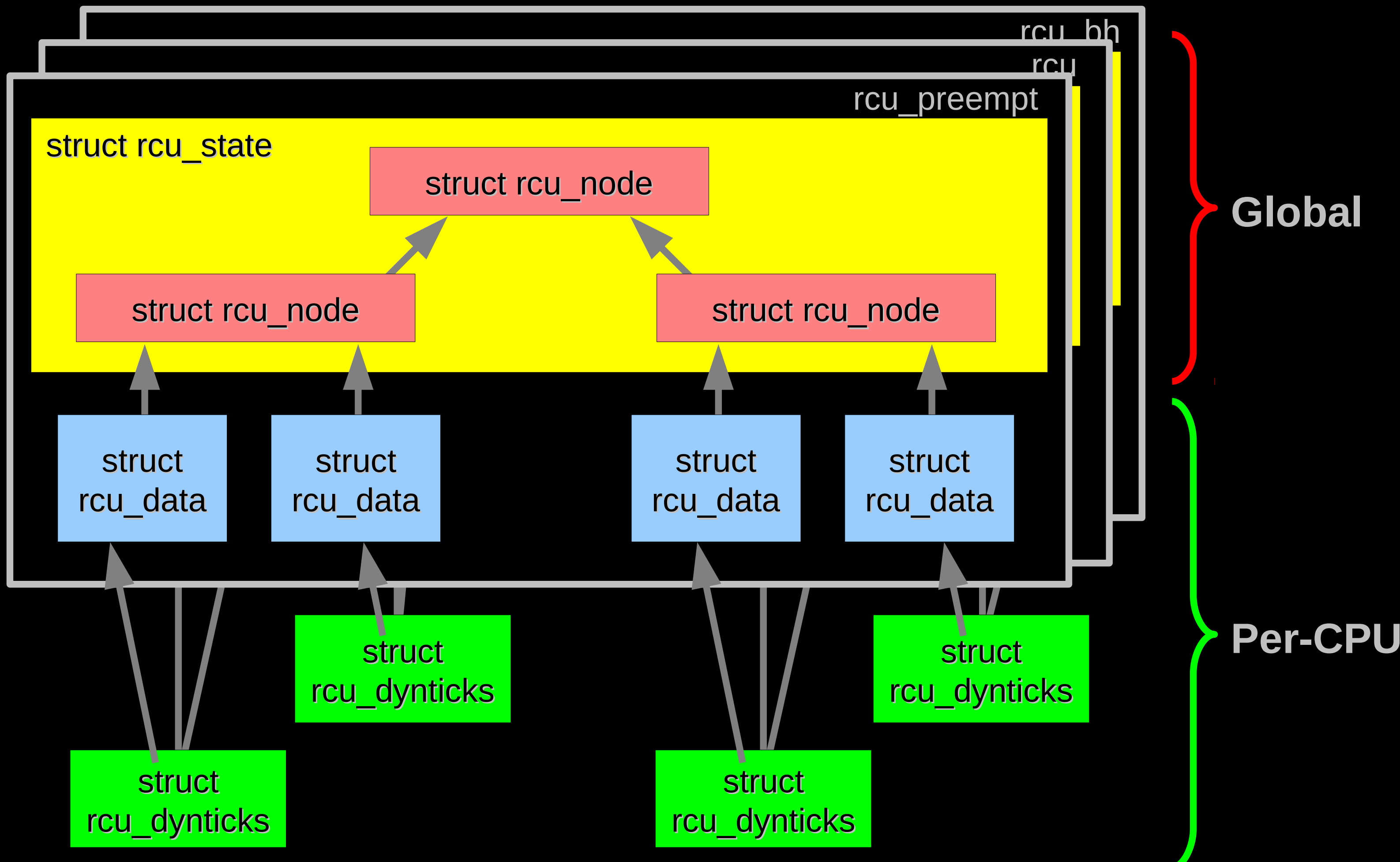
- Understand the Workloads
  - Which for Linux means a great many of them
  - Your code must handle whatever shows up
- Google-Search LWN
  - But you knew this already
- Test Unfamiliar Primitives
  - And complain on LKML if they break
  - Preferably accompanying the complaint with a fix
- Review Others' Code
  - See Documentation directory for how-to info
- Make a Map
  - See next slides...

Making a Map of Software

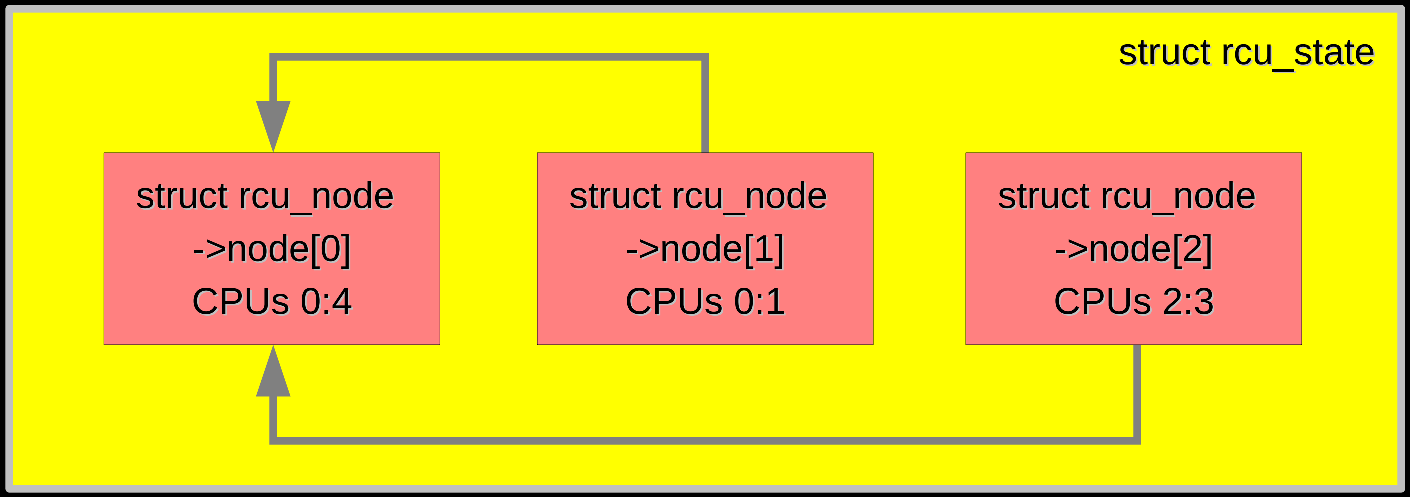
Hierarchical RCU Data Structures

```
struct rcu_dynticks {
  int dynticks_nesting;
  int dynticks;
  int dynticks_nmi;
};

struct rcu_node {
  spinlock_t lock;
  long  gpnum;
  long  completed;
  unsigned long qsmask;
  unsigned long qsmaskinit;
  unsigned long grpmask;
  int  grplo;
  int  grphi;
  u8  grpnum;
  u8  level;
  struct rcu_node *parent;
  struct list_head blocked_tasks[2];
}

struct rcu_data {
  long    completed;
  long    gpnum;
  long    passed_quiesc_completed;
  bool    passed_quiesc;
  bool    qs_pending;
  bool    beenonline;
  bool    preemptable;
  struct rcu_node *mynode;
  unsigned long grpmask;
  struct rcu_head *nxtlist;
  struct rcu_head **nxttail[RCU_NEXT_SIZE];
  long    qlen;
  long    qlen_last_fqs_check;
  unsigned long  n_force_qs_snap;
  long    blimit;
#ifdef CONFIG_NO_HZ
  struct rcu_dynticks *dynticks;
  int dynticks_snap;
  int dynticks_nmi_snap;
#ifdef CONFIG_NO_HZ
  unsigned long dynticks_fqs;
#endif /* #ifdef CONFIG_NO_HZ */
  unsigned long offline_fqs;
  unsigned long resched_ipi;
  long n_rcu_pending;
  long n_rp_qs_pending;
  long n_rp_cb_ready;
  long n_rp_cpu_needs_gp;
  long n_rp_gp_completed;
  long n_rp_gp_started;
  long n_rp_need_fqs;
  long n_rp_need_nothing;
  int cpu;
};

struct rcu_state {
  struct rcu_node node[NUM_RCU_NODES];
  struct rcu_node *level[NUM_RCU_LVLS];
  u32 levelcnt[MAX_RCU_LVLS + 1];
  u8 levelspread[NUM_RCU_LVLS];
  struct rcu_data *rda[NR_CPUS];
  u8  signaled;
  long  gpnum;
  long  completed;
  spinlock_t onofflock;
  struct rcu_head *orphan_cbs_list;
  struct rcu_head **orphan_cbs_tail;
  long orphan_qlen;
  spinlock_t fqslock;
  unsigned long jiffies_force_qs;
  unsigned long n_force_qs;
  unsigned long n_force_qs_lh;
  unsigned long n_force_qs_ngp;
#ifdef CONFIG_RCU_CPU_STALL_DETECTOR
  unsigned long gp_start;
  unsigned long jiffies_stall;
#endif /* #ifdef CONFIG_RCU_CPU_STALL_DETECTOR */
  long dynticks_completed;
};
```

Mapping Data Structures



Placement of rcu_node Within rcu_state



Avoiding Bugs By Process

Avoiding Bugs By Process

- Review your own work carefully
  - See following slides
- Test early, test often, test in small pieces
  - Debugging is 2-3 times harder than writing code
  - Problem-isolation effort rises as the square of the code size
- Where possible, use existing well-tested code
  - Even if it is a lot more fun to re-invent the wheel
- I would have rejected this advice as late as the early 1990s, but have since learned the hard way to accept it
- But I still sometimes has difficulty following it:
  - http://paulmck.livejournal.com/14639.html

Review Your Own Code Carefully

- Paul E. McKenney's self-review rules for complex code:
  - Write the code long hand in pen on paper
  - Correct bugs as you go
  - Copy onto a clean sheet of paper
  - Repeat until the last two versions are identical

- What constitutes “not complex”?
  - Sequential code, *and*
  - You test it incrementally
    - For example, bash script or single-threaded C-code with gdb
  - If feasible, you test it exhaustively

just after "if" in "do-while"
in __rcu_offline_cpu()

```
static void rcu_preempt_offline_tasks(struct rcu_state *rsp,
                                      struct rcu_node *rnp){
{
```

acquire root rcu_node lock, migrate tasks, (blocked_tasks)
updating their pointers...

--> also fix lock acqu. in rcu_read_unlock_special

put them all on current index of root node
(safe, simple) ← comment which is current -- (the one indexed by low bit of gpnum)

or copy straight same index!!!

⟹ and fix ctxt-switch stuff to check lock after acq.

```
static void rcu_preempt_offline_tasks(struct rcu_state *rsp,
                                      struct rcu_node *rnp)
{
        struct rcu_node *rnproot = rcu_get_root();
        if (!list_empty      struct task_struct *tp;    stet
        int i;                 struct list_head *lp;    stet
        if (rnp == rnproot()) return;
        for (i = 0; i < 2; i++) {   lp =
                while
                if (!list_empty(&rnp->blocked_tasks[i])) {
                        continue;
                                       safe
                        list_for_each_entry(tp, &rnp->
                        tp = list_entry(
```

```
static void rcu_preempt_offline_tasks(struct rcu_state *rsp,
                                      struct rcu_node *rnp)
{
        int i;
        struct list_head *lp;
        struct list_head *lp_root;
        struct rcu_node *rnp_root = rcu_get_root(rsp);
        struct task_struct *tp;

        if (rnp == rnp_root)
                return;

        for (i = 0; i < 2; i++) {
                lp = &rnp->blocked_tasks[i];
                lp_root = &rnp_root->blocked_tasks[i];
                while (!list_empty(lp)) {
                        tp = list_entry(lp->next, typeof(*tp),
                                        rcu_node_entry);
                        spin_lock(&rnp_root->lock); /* irqs disabled */
                        list_del(&tp->rcu_node_entry);
                        list_add(&tp->rcu_node_entry, lp_root);
                        tp->rcu_blocked_node = rnp_root;
                        spin_unlock(&rnp_root->lock); /* irqs disabled */
                }
        }
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                        tp->rcu_blocked_node = rnp_root;
                        spin_unlock(&rnp_root->lock); /* irqs disabled */
                }
        }
}
```

So, How Well Did I Do?

```
static void rcu_preempt_offline_tasks(struct rcu_state *rsp,
              struct rcu_node *rnp,
              struct rcu_data *rdp)
{
  int i;
  struct list_head *lp;
  struct list_head *lp_root;
  struct rcu_node *rnp_root = rcu_get_root(rsp);
  struct task_struct *tp;

  if (rnp == rnp_root) {
    WARN_ONCE(1, "Last CPU thought to be offlined?");
    return;
  }
  WARN_ON_ONCE(rnp != rdp->mynode &&
         (!list_empty(&rnp->blocked_tasks[0]) ||
          !list_empty(&rnp->blocked_tasks[1])));
  for (i = 0; i < 2; i++) {
    lp = &rnp->blocked_tasks[i];
    lp_root = &rnp_root->blocked_tasks[i];
    while (!list_empty(lp)) {
      tp = list_entry(lp->next, typeof(*tp), rcu_node_entry);
      spin_lock(&rnp_root->lock); /* irqs already disabled */
      list_del(&tp->rcu_node_entry);
      tp->rcu_blocked_node = rnp_root;
      list_add(&tp->rcu_node_entry, lp_root);
      spin_unlock(&rnp_root->lock); /* irqs remain disabled */
    }
  }
}
```

```
static int rcu_preempt_offline_tasks(struct rcu_state *rsp,
                                     struct rcu_node *rnp,
                                     struct rcu_data *rdp)
{
  int i;
  struct list_head *lp;
  struct list_head *lp_root;
  int retval;
  struct rcu_node *rnp_root = rcu_get_root(rsp);
  struct task_struct *tp;

  if (rnp == rnp_root) {
    WARN_ONCE(1, "Last CPU thought to be offlined?");
    return 0;  /* Shouldn't happen: at least one CPU online. */
  }
  WARN_ON_ONCE(rnp != rdp->mynode &&
         (!list_empty(&rnp->blocked_tasks[0]) ||
          !list_empty(&rnp->blocked_tasks[1])));
  retval = rcu_preempted_readers(rnp);
  for (i = 0; i < 2; i++) {
    lp = &rnp->blocked_tasks[i];
    lp_root = &rnp_root->blocked_tasks[i];
    while (!list_empty(lp)) {
      tp = list_entry(lp->next, typeof(*tp), rcu_node_entry);
      spin_lock(&rnp_root->lock); /* irqs already disabled */
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    }
  }
  return retval;
}
```

More changes due to RCU priority boosting

When Does This Approach Fail to Avoid Bugs?

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- Excessive schedule pressure rules out this approach
- Excessive optimism about understanding of surrounding hardware and software
  - Limitations of in_irq()
  - “Interesting” properties of user-mode helpers: Entering exception handlers then never leaving them
- Excessive optimism about understanding of requirements
  - “It is only a few microseconds added latency!!!”
  - “It is only a few extra scheduler-clock interrupts!!!”
  - “It won't degrade scalability up to at least eight CPUs!!!”
- Excessive optimism about understanding of algorithm
  - “That cannot possibly happen!!!”
- But without excessive optimism, we would never start anything...

Avoiding Bugs By Mechanical Proofs

Avoiding Bugs By Mechanical Proofs

- Works well for small, self-contained algorithms
  - http://lwn.net/Articles/243851/ (QRCU)
  - http://lwn.net/Articles/279077/ (RCU dynticks I/F)
  - git://lttng.org/userspace-rcu formal-model (URCU)
- However, the need for formal proof often indicates an overly complex design!!!
  - Preemptible RCU's dynticks interface being an extreme case in point (http://lwn.net/Articles/279077/)
- And you cannot prove your proof's assumptions...

Avoiding Bugs By Statistical Analysis

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- Different kernel configuration options select different code
- Suppose that more failure occur with CONFIG_FOO=y
  - Focus inspection on code under #ifdef CONFIG_FOO
- But what exactly does “more failures” mean?

Avoiding Bugs By Statistical Analysis

- Different kernel configuration options select different code
- Suppose that more failure occur with CONFIG_FOO=y
  - Focus inspection on code under #ifdef CONFIG_FOO
- But what exactly does “more failures” mean?
  - That is where the statistical analysis comes in
  - The “more failures” must be enough more to be statistically significant
  - One of the most useful classes I took as an undergraduate was a statistics course!

Coping With Schedule Pressure

Coping With Schedule Pressure

- When you are fixing a critical bug, speed counts
- The difference is level of risk
  - The code is *already* broken, so there is less benefit from using extremely dainty process steps (exceptions?)
  - But *only* if you follow up with careful process
  - Which I repeatedly learn the hard way: http://paulmck.livejournal.com/14639.html
  - Failure to invest a few days in early 2009 cost me more than a month in late 2009!!!
- Long-term perspective required
  - And that means *you* – leave the “blame it on management” game to Dilbert cartoons
  - Align with management initiatives, for example, “agile development”

But I Did All This And There Are Still Bugs!!!

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- “Be Careful!!! It Is A Real World Out There!!!”
  - Might your program be non-trivial?
- The purpose of careful software-development practices is to reduce risk
  - Strive for perfection, but understand that this goal is rarely reached in this world

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- **But you still need to fix your bugs!!!**

Fixing Bugs

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  - So your job is to make it tell you!
- Ways to make the computer tell you where the bugs are:
  - Debugging printk()s and assertions
  - Event tracing and ftrace
  - Lock dependency checker (CONFIG_PROVE_LOCKING and CONFIG_PROVE_RCU)
  - Static analysis (and pay attention to compiler warnings!!!)
  - Structured testing: Use an experimental approach
  - **Record all test results, including environment**

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  - But getting another person's viewpoint can be helpful
    - To 10,000 *educated and experienced* eyes, all bugs are shallow
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- Gaining other people's viewpoints
  - Have other people review your code
  - Explain your code to someone else
  - Special case of explaining code: Document it
    - Think of questions you might ask if someone else showed you the code
    - Focus on the parts of the code you are most proud of: Most likely buggy!
    - Try making a copy of the code, removing the comments, and then documenting it: Perhaps the comments are confusing you

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- Event tracing for RCU: 35MB of trace events for each failure
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- What to do?

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- What to do? Scripting!!!
- How to generate useful scripts:
  - Do it by hand the first few times
  - But keep detailed notes on what you did and what you found
  - Incrementally construct scripts to carry out the most laborious tasks
  - Eventually, you will have a script that analyzes the failures
- But suppose you are working on many different projects?

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  - Eventually, you will have a script that analyzes the failures
- But suppose you are working on many different projects?
  - Script the common cases that occur in many projects
  - Take advantage of tools others have constructed

Summary and Conclusions

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- Avoid Bugs By Process
- Avoid Bugs By Mechanical Proofs
- Avoid Bugs By Statistical Analysis
- Avoid Schedule Pressure via Long-Term View
- But Even If You Do All This, There Will Still Be Some Bugs (http://lwn.net/Articles/453002/)
  - Yes, you are living in the real world!!!
  - Might be painful sometimes, but it sure beats all known alternatives...

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Questions?