Live Patching

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Live (Kernel/User space) Patching

- **What is it?**
  - Application of kernel patches without stopping/rebooting the system
  - Similarly applies to the user space

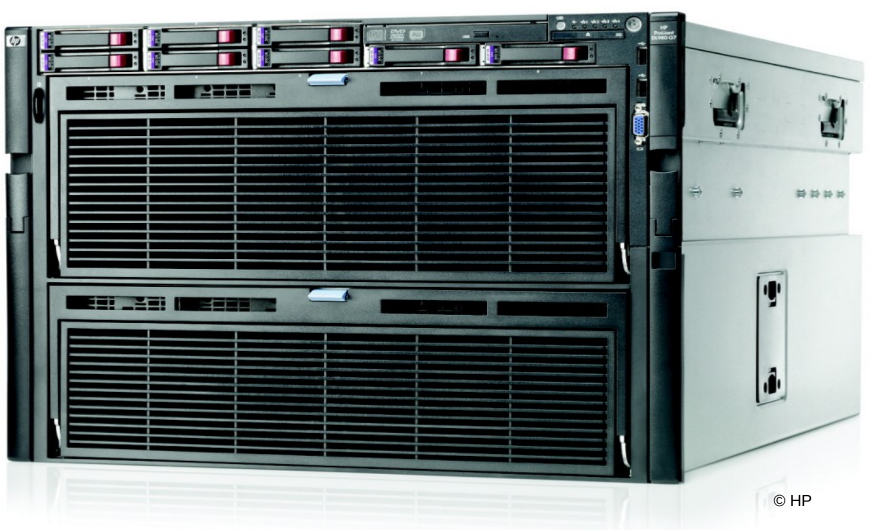
- **Why?**
  - Convenience/Cost – Huge cost of downtime, hard to schedule
  - Availability
  - Compliance

- **Clear goal – reduce planned or unplanned downtime**

Barcelona Supercomputing Center

- 165k Skylake cores
- Terabytes of data
- Reboot?

SAP HANA



HP DL980 w/ 12 TB RAM

- **In-memory database and analytics engine**
- **4-16 TB of RAM**
- **All operations done in memory**
- **Disk used for journalling**
- **Active-Passive HA**
- **Failover measured in seconds**
- **Reboot?**

Goals and Principles

- **Applying limited scope fixes to the Linux kernel**
  - Security, stability and corruption fixes
- **Require minimal changes to the source code**
  - Limited changes outside of the infrastructure itself
- **Have no runtime performance impact**
  - Full speed of execution
- **No interruption of applications while patching**
  - Full speed of execution
- **Allow full review of patch source code**
  - For accountability and security purposes

History

- **Windows HotPatching (2003 – Microsoft)**
  - Stops kernel execution for activeness check (busy loop)
  - A function redirection using a short jump before a function prologue
- **Ksplice (2008 – MIT, Oracle)**
  - First to patch the Linux kernel
  - Stops kernel execution for activeness check
    - Restarts and tries again later when active
  - Uses jumps patched into functions for redirection
- **kpatch (2014 – RedHat)**
  - Similar to Ksplice
  - Binary patching
- **kGraft (2014 – SUSE)**
  - Immediate patching with lazy migration
  - Per-thread consistency model

Kernel Live Patching in Linux Upstream

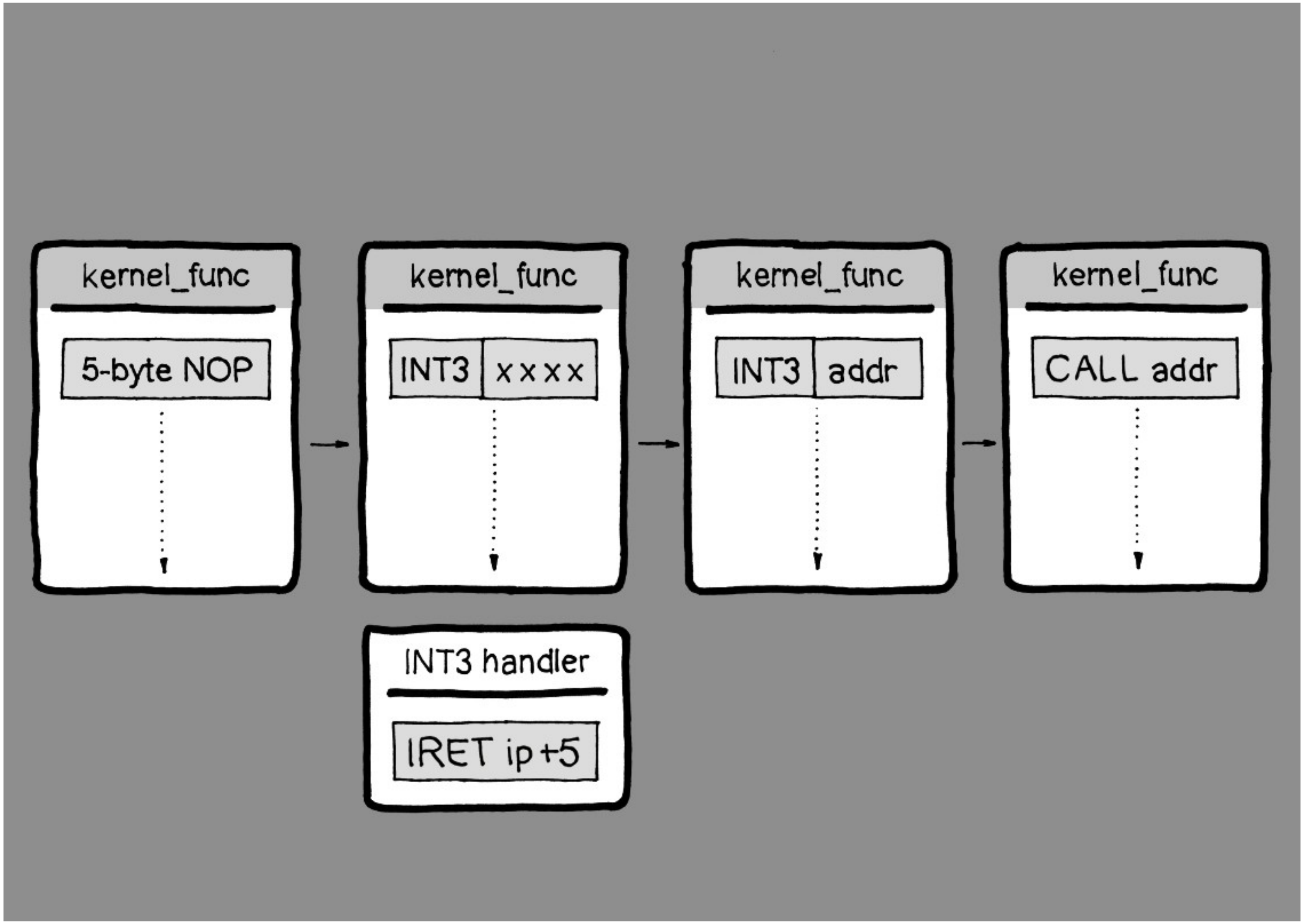
- **Result of a discussion between Red Hat and SUSE at Linux Plumbers Conference 2014 in Dusseldorf**
- **Basic infrastructure**
  - Neither kGraft, nor kpatch
  - Patch format abstraction and function redirection based on ftrace
  - x86_64, s390x and powerpc architectures supported
    - arm64 in development
- **Merged to 4.0 in 2015**

Call Redirection

- **x86_64 from now on**
  - Although s390x, powerpc and arm64 are similar

- **Use of ftrace framework**
  - `gcc -pg` is used to generate calls to **`_fentry_()`** at the beginning of every function
  - ftrace replaces each of these calls with **`NOP`** during boot, removing runtime overhead (when CONFIG_DYNAMIC_FTRACE is set)
  - When a tracer registers with ftrace, the **`NOP`** is runtime patched to a **`CALL`** again
  - livepatch uses a tracer, too, but then asks ftrace to change the return address to the new function
  - And that's it, call is redirected

Call Redirection



Simple Sample

```
static int cmdline_proc_show(struct seq_file *m, void *v)
{
        seq_printf(m, "%s\n", saved_command_line);
        return 0;
}
```

Call Redirection

```
<cmdline_proc_show>:
e8 4b 68 39 00          callq  ffffffff8160d8d0 <__fentry__>
48 8b 15 7c 3f ef 00    mov    0xef3f7c(%rip),%rdx   # <saved_command_line>
31 c0                   xor    %eax,%eax
48 c7 c6 a3 d7 a4 81    mov    $0xffffffff81a4d7a3,%rsi
e8 e6 1d fb ff          callq  ffffffff81228e80 <seq_printf>
31 c0                   xor    %eax,%eax
c3                      retq
0f 1f 00                nopl   (%rax)
```

Call Redirection

```
<cmdline_proc_show>:
e8 4b 68 39 00          callq  ffffffff8160d8d0 <__fentry__>
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31 c0                   xor    %eax,%eax
c3                      retq
0f 1f 00                nopl   (%rax)

<cmdline_proc_show>:
0f 1f 44 00 00          nopl   0x0(%rax,%rax,1)
48 8b 15 7c 3f ef 00    mov    0xef3f7c(%rip),%rdx   # <saved_command_line>
```

Call Redirection

```
<cmdline_proc_show>:
e8 4b 68 39 00          callq  ffffffff8160d8d0 <__fentry__>
48 8b 15 7c 3f ef 00    mov    0xef3f7c(%rip),%rdx   # <saved_command_line>
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<cmdline_proc_show>:
e8 7b 3f e5 1e          callq  0xffffffffa00cb000    # ftrace handler
48 8b 15 7c 3f ef 00    mov    0xef3f7c(%rip),%rdx   # <saved_command_line>
```
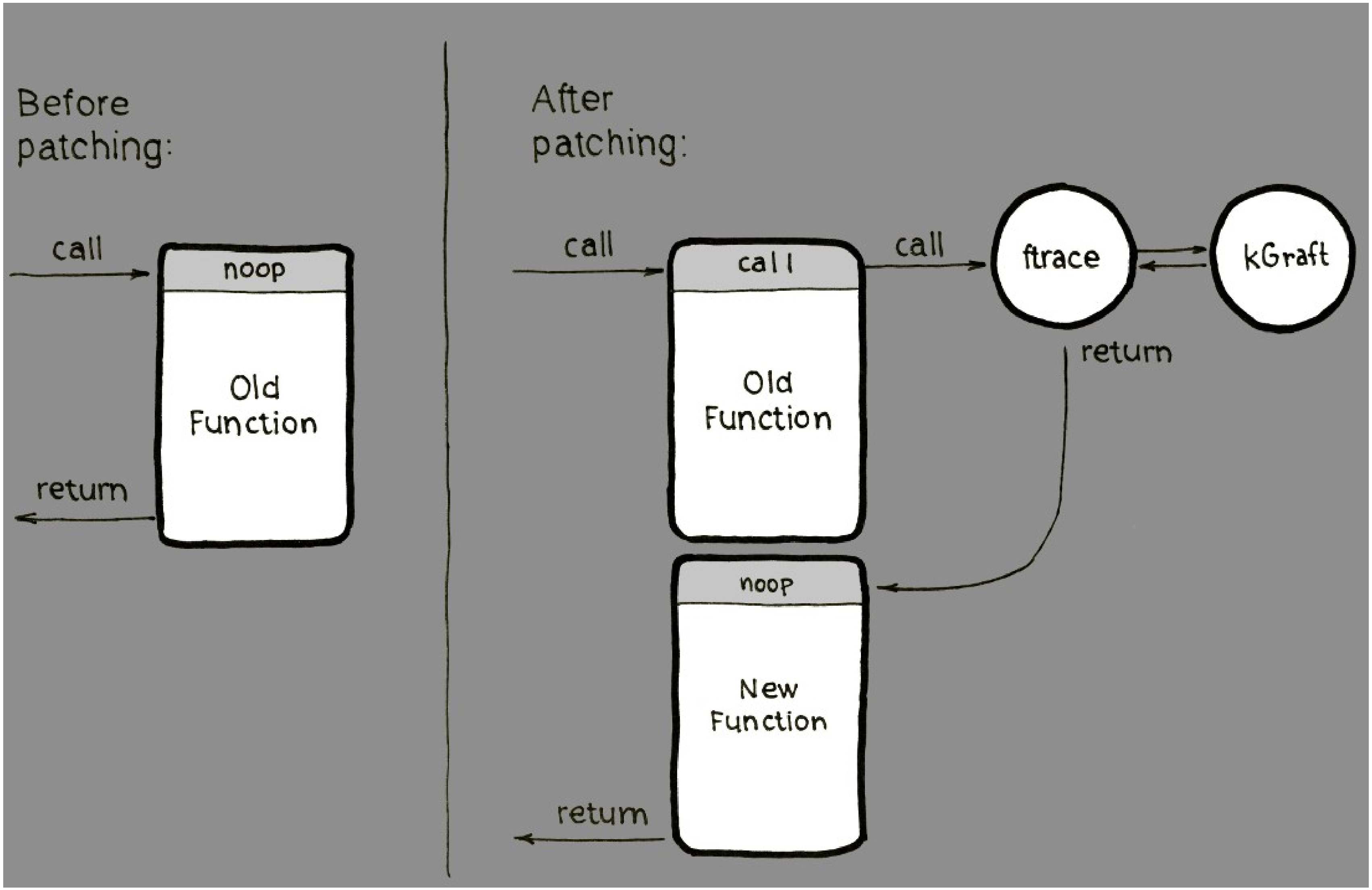

Call Redirection



```
static int livepatch_cmdline_proc_show(struct seq_file *m, void *v)
{
        seq_printf(m, "%s\n", "this has been live patched");
        return 0;
}

static struct klp_func funcs[] = {
        {
          .old_name = "cmdline_proc_show",
          .new_func = livepatch_cmdline_proc_show,
        }, { }
};
static struct klp_object objs[] = {
        { /* name being NULL means vmlinux */
          .funcs = funcs, },
        { }
};
static struct klp_patch patch = { .mod = THIS_MODULE, .objs = objs, };

static int livepatch_init(void)
{
        return klp_enable_patch(&patch);
}
static void livepatch_exit(void) { }

module_init(livepatch_init);
module_exit(livepatch_exit);
MODULE_LICENSE("GPL");
MODULE_INFO(livepatch, "Y");
```

Patch Generation – Semi-automatic Approach

- **Patches were originally created entirely by hand**
  - Create a list of functions to be replaced
  - Copy the source code, fix it
  - Code closure to make it compile
  - Call livepatch: klp_enable_patch()
  - Compile, insert as .ko module, done
- **The source of the patch is then a single C file**
  - Easy to review, easy to maintain in a VCS like git
- **klp-ccp**
  - https://github.com/SUSE/klp-ccp
  - Prepares a C file almost automatically

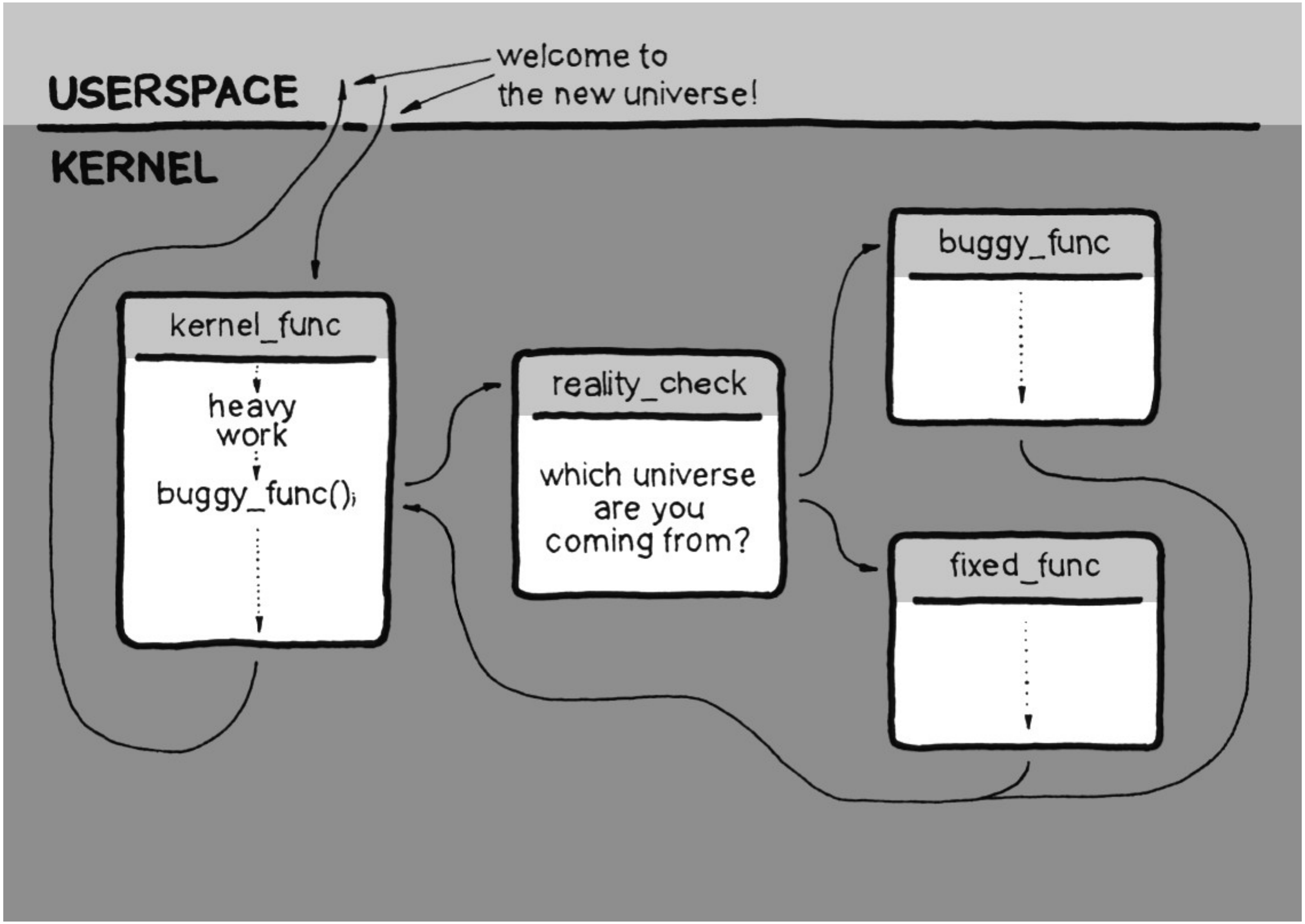
Call Redirection – The Final Hurdle

- **Changing a single function is easy**
  - Since ftrace patches at runtime, you just flip the switch
- **What if a patch contains multiple functions that *depend* on each other?**
  - Number of arguments changes
  - Types of arguments change
  - Return type change
  - Or semantics change
- **We need a consistency model**

kGraft Consistency Model

- **Avoid calling a new function from old and vice versa**
- **Make sure a thread calls either all old functions or all new**
- **Migrate them one by one to 'new' as they enter/exit execution**
- **No stopping for anybody**

kGraft Consistency Model



kGraft Consistency Model

- **Per-thread flag**
  - TIF_KGR_IN_PROGRESS
- **Mark all tasks in a system at the beginning and wait for them to be migrated to a new universe**
- **Finalize**

kGraft Consistency Model

- **How about eternal sleepers?**
  - Like `getty` on a console 10
  - They'll never exit the kernel
  - They'll never be migrated to 'new'
  - They'll block completion of the patching process forever

- **Wake them up!**
  - Sending a *fake signal* (SIGPENDING flag, but no signal in a queue)
  - The signal exits the syscall and transparently restarts it

- **And kthreads?**
  - They cannot exit the kernel ever
  - Annotate them in a safe place and wake them up

kpatch Consistency Model

- **First `stop_kernel();`**
  - That stops all CPUs completely, including all applications
- **Then, check all stacks, whether any thread is stopped within a patched function**
- **If yes, resume kernel and try again later**
  - And hope it'll be better next time
- **If not, flip the switch on all functions and resume the kernel**
- **The system may be stopped for 10-40ms typical**

Livepatch Hybrid Consistency Model

- **Hybrid of kGraft and kpatch consistency models**
- **Based on a stack checking**
- **Heated discussion when proposed**
  - Stacks and their dumps are unreliable
- **Josh Poimboeuf then proposed objtool**
  - It analyzes every .o file and ensures the validity of its stack metadata (frame pointer usage at the time of proposal)
- **The second proposal sidetracked as well**
  - Josh rewrote the kernel stack unwinder
- **Merged to 4.12**
  - The pure kGraft is not present in any supported code stream of SUSE Linux Enterprise Server

Livepatch Hybrid Consistency Model

- **Per-thread migration, but scope limited to a set of patched functions**
- **What entity the execution must be outside of to be able to make the switch**
  - LEAVE_{FUNCTION, PATCHED_SET, KERNEL}
- **What entity the switch happens for**
  - SWITCH_{FUNCTION, THREAD, KERNEL}
- **kGraft is LEAVE_KERNEL and SWITCH_THREAD**
- **kpatch is LEAVE_PATCHED_SET and SWITCH_KERNEL**
- **Hybrid consistency model is LEAVE_PATCHED_SET and SWITCH_THREAD**
  - Reliable, fast-converging, no annotation of kernel threads, no failure with frequent sleepers

Livepatch Hybrid Consistency Model

- **Stack checking**
  - To ensure that a task does not sleep in a to-be-patched function (set of to-be-patched functions)
- **Per-thread flag**
  - Similar to kGraft
  - Threads are still migrated on the user space/kernel space boundary
- **Allows for faster migration to a new universe**

Livepatch Hybrid Consistency Model

- **Slightly different consistency model leads to slight differences during a live patch development**
  - Threads are switched earlier (when they leave patched set)
  - It could matter in case of complex caller–callee changes
- **Eternal sleepers**
  - Not a problem as long as they do not sleep in a patched function (set of patched functions)
  - We have the fake signal for the rest
- **Kthreads are the same**

Livepatch Hybrid Consistency Model

- **Reliable stacks require frame pointers (FPs)**
  - There is a performance penalty with FPs enabled
- **Plans to add Call Frame Information (CFI, DWARF) validation for C files, CFI generation for assembly files and introduction of DWARF-aware unwinder were not welcome**
- **ORC unwinder**
  - Tailored info generated by objtool
  - Unwinder is simple – no complicated state machine

```
static void notrace klp_ftrace_handler(unsigned long ip, unsigned long parent_ip, struct
                                       ftrace_ops *fops, struct pt_regs *regs)
{
        struct klp_ops *ops;
        struct klp_func *func;
        int patch_state;

        ops = container_of(fops, struct klp_ops, fops);
        preempt_disable_notrace();
        func = list_first_or_null_rcu(&ops->func_stack, struct klp_func,
                                      stack_node);
        if (WARN_ON_ONCE(!func))
                goto unlock;
        smp_rmb();

        if (unlikely(func->transition)) {
                smp_rmb();
                patch_state = current->patch_state;
                WARN_ON_ONCE(patch_state == KLP_UNDEFINED);

                if (patch_state == KLP_UNPATCHED) {
                        func = list_entry_rcu(func->stack_node.next,
                                              struct klp_func, stack_node);
                        if (&func->stack_node == &ops->func_stack)
                                goto unlock;
                }
        }
        if (func->nop)
                goto unlock;
        klp_arch_set_pc(regs, (unsigned long)func->new_func);
unlock:
        rcu_read_unlock();
}
```

Additional Features

- **Callbacks**
  - klp_object (un)patching notification mechanism
  - Modification of global data and registration of newly available services/handlers
- **Shadow variables**
  - Way to deal with data structure/semantics changes
  - Associating a new field to the existing structure
- **Selftests and samples**

Atomic Replace

- **Livepatch allows multiple patches on a (function) stack**
- **Maintenance nightmare if there is a dependency between patches**
  - Several different fixes of a function

- **Cumulative patches and atomic replace**
  - All older patches removed after the transition
  - Special nop functions which redirect to the original functions

Limitations and Missing Features

- **Non-exported symbols**
  - kallsyms trick
  - Relocations
  - klp-convert
- **Patch creation tool**
  - Currently semi-automatic, tools to help
  - kpatch-build
  - Source-based approach in upstream

Limitations and Missing Features

- **GCC optimizations**
  - Inlining
    - A bug propagation
  - Interprocedural optimizations

  - GCC to help
    - -fdump-ipa-clones
    - -flive-patching

Userspace Live Patching

- **Libpulp**
  - https://github.com/SUSE/libpulp
  - Library for live patching other user space libraries
  - Ptrace-based

- **Consistency model**
  - Similar to the original kGraft approach
  - Per-thread
  - Migration on the application-library boundary

- **In development but definitely coming**

- **Youtube recording from SUSE Labs Conference 2020**

We adapt. You succeed.