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Static Previrtualization[1]

N. Shankar

Computer Science Laboratory
SRI International
Menlo Park, CA

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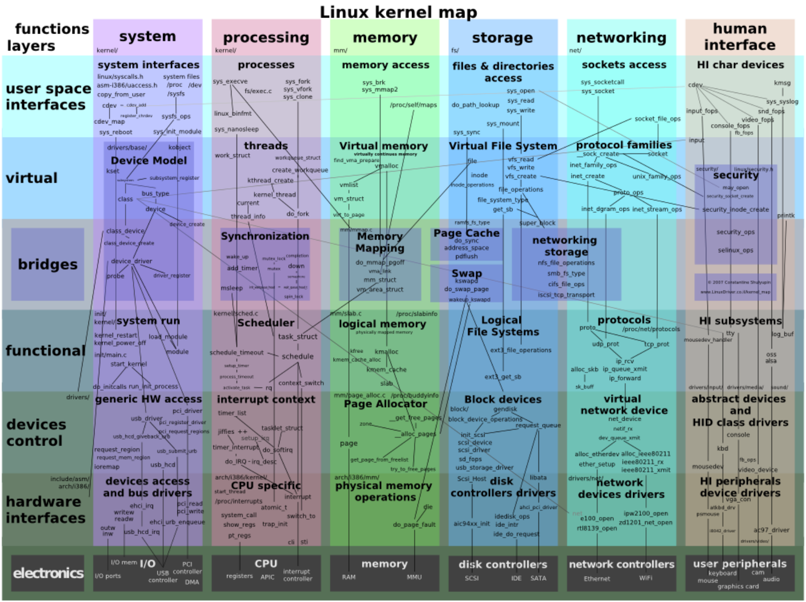
The View from the Top

- The modern hardware/software/communication stack is an unprecedented success.
- Complex applications are now easier to write.
- But this simplicity comes at a cost
  - **MiniBlog** – "Simple" PHP blogging application
    - 683 lines of PHP code
    - Depends on PHP & MySQL
  - **PHP** – Programming language interpreter
    - 625,000 lines of C
    - Depends on LibC
  - **LibC** – C standard runtime library
    - 650,000 lines of C
    - Depends on Linux kernel
  - **Linux Kernel** – Operating System
    - 15 million lines of code!

A House of Cards? [Wikipedia]



Linux kernel map

functions layers | system kernel/ | processing kernel/ | memory mm/ | storage fs/ | networking net/ | human interface

user space interfaces
- system interfaces: linux/syscalls.h, asm-i386/uaccess.h, copy_from_user, system files /proc /dev /sysfs, cdev, cdev_add, cdev_map, register_chrdev, sysfs_ops, sys_reboot, sys_init_module
- processes: sys_execve, fs/exec.c, sys_fork, sys_vfork, sys_clone, linux_binfmt, sys_nanosleep
- memory access: sys_brk, sys_mmap2, /proc/self/maps
- files & directories access: sys_open, sys_read, sys_write, do_path_lookup, sys_mount, sys_sync
- sockets access: sys_socketcall, sys_socket, socket_file_ops
- HI char devices: cdev, kmsg, sys_syslog, input_fops, snd_fops, video_fops, console_fops, fb_fops, input

virtual
- Device Model: drivers/base/, kobject, kset, subsystem_register, bus_type, class, device, device_create
- threads: work_struct, workqueue_struct, create_workqueue, kthread_create, kernel_thread, current, thread_info, do_fork
- Virtual memory: virtually continuous memory, find_vma_prepare, vmalloc, vmlist, vm_struct, virt_to_page
- Virtual File System: file, vfs_read, vfs_write, inode, vfs_create, inode_operations, file_operations, file_system_type, get_sb
- protocol families: sock_create, socket, inet_family_ops, inet_create, unix_family_ops, proto_ops, inet_dgram_ops, inet_stream_ops
- security: security/, linux/security.h, may_open, security_socket_create, security_inode_create, printk

bridges
- class_device, class_device_create, device_driver, probe, driver_register
- Synchronization: wake_up, mutex_lock, completion, add_timer, mutex, down, semaphore, msleep, spin_lock
- Memory Mapping: mm/mmap.c, do_mmap_pgoff, vma_link, mm_struct, vm_area_struct
- Page Cache: do_sync, address_space, pdflush
- Swap: kswapd, do_swap_page, wakeup_kswapd
- ramfs_fs_type, super_block
- networking storage: nfs_file_operations, smb_fs_type, cifs_file_ops, iscsi_tcp_transport
- security_ops, selinux_ops
- © 2007 Constantine Shulyupin www.LinuxDriver.co.il/kernel_map

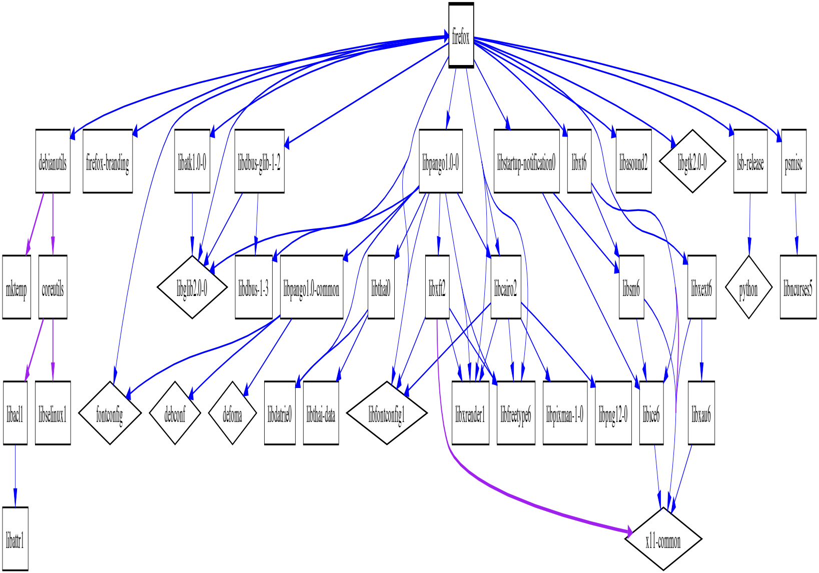
functional
- system run: init/, kernel/, kernel_restart, kernel_power_off, load_module, module, init/main.c, start_kernel, do_initcalls, run_init_process
- Scheduler: kernel/sched.c, task_struct, schedule_timeout, schedule, setup_timer, process_timeout, activate_task, rq, context_switch
- logical memory: mm/slab.c, /proc/slabinfo, physically mapped memory, kfree, kmalloc, kmem_cache_alloc, kmem_cache, slab
- Logical File Systems: ext3_file_operations, ext3_get_sb
- protocols: proto, /proc/net/protocols, udp_prot, tcp_prot, ip_rcv, alloc_skb, ip_queue_xmit, ip_forward, sk_buff
- HI subsystems: tty, log_buf, mousedev_handler, oss, alsa

devices control
- drivers/, generic HW access: pci_driver, usb_driver, pci_register_driver, pci_request_regions, usb_hcd_giveback_urb, request_region, request_mem_region, usb_submit_urb, ioremap, usb_hcd
- interrupt context: timer_list, tasklet_struct, jiffies ++, setup_irq, timer_interrupt, do_softirq, do_IRQ, irq_desc
- Page Allocator: mm/page_alloc.c, /proc/buddyinfo, get_free_pages, zone, alloc_pages, page, get_page_from_freelist, try_to_free_pages
- Block devices: block/, gendisk, block_device_operations, request_queue, init_scsi, scsi_device, scsi_driver, sd_fops, usb_storage_driver
- virtual network device: net_device, netif_rx, dev_queue_xmit, alloc_etherdev, alloc_ieee80211, ether_setup, ieee80211_rx, ieee80211_xmit
- abstract devices and HID class drivers: drivers/input/, drivers/media/, sound/, console, kbd, fb_ops, mousedev, video_device

hardware interfaces
- devices access and bus drivers: include/asm/, arch/i386/, ehci_irq, pci_read, writew, pci_write, readw, ehci_urb_enqueue, outw, inw, usb_hcd_irq
- CPU specific: arch/i386/kernel/, start_thread, /proc/interrupts, interrupt, atomic_t, system_call, switch_to, show_regs, trap_init, pt_regs, cli, sti
- physical memory operations: arch/i386/mm/, die, do_page_fault
- disk controllers drivers: Scsi_Host, libata, ahci_pci_driver, idedisk_ops, aic94xx_init, ide_intr, ide_do_request
- network devices drivers: drivers/net/, e100_open, ipw2100_open, zd1201_net_open, rtl8139_open
- HI peripherals device drivers: vga_con, atkbd_drv, psmouse, i8042_driver, ac97_driver, drivers/video/

electronics
- I/O: I/O mem, I/O ports, PCI controller, USB controller, DMA
- CPU: registers, APIC, interrupt controller
- memory: RAM, MMU
- disk controllers: SCSI, IDE, SATA
- network controllers: Ethernet, WiFi
- user peripherals: keyboard, mouse, cam, audio, graphics card

Firefox Package Dependencies



The Problem

- Software stack growing in size
  - More functionality
  - More hardware supported
  - Diverse application needs
  - Complex and numerous device drivers
  - Less robust to change
- Adverse security implications
  - More code to analyze
  - Increasingly complex interactions
  - Same time-to-market

    →

    - Reduced relative code coverage
    - Greater diversity of exploits
    - Wider attack surface
    - Larger consequences

Static Previrtualization: A Principled Approach

- Shrink the software by specializing it to a specific deployment
- Target full software stack and address all code growth.
- Specialize software stack to
    - Specific applications
    - Specific hardware/deployment configuration
        - Kernel modules trimmed
        - Device drivers trimmed
        - Libraries trimmed
- Applicable to
    - Specialized application servers
    - Custom libraries

Comparison

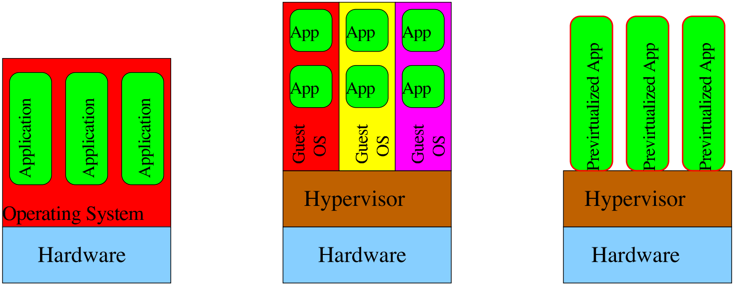


Figure 1: Single OS systems, Virtualized Systems, and Previrtualized Systems

Partial Evaluation

- A practical application of Kleene's s-m-n theorem for optimizating code by specializing it to specific arguments

-
  ```
  int atoi_strcat(char *str1, char *str2){
    return atoi(strcat(str1, str2));
  }
    ...
    char *pad = "000";
    i = atoi_strcat(mystr, pad);
  ```

- The `atoi_strcat` invocation can be replaced by

  ```
    atoi_strcat_1000(argv[1])
  ```

  where

  ```
  int atoi_strcat_1000(char *str1){
    return 1000 * atoi(str1);
  }
  ```

Partial Evaluation

- Fixes specific parameters
    - Interpreter + program → object code
    - Specializer + interpreter → compiler
    - Specializer + specializer → compiler-compiler
- Partial evaluation of common system calls
    - Improved performance (*McNamee, 2001*)
- Customized runtimes via partial evaluation
    - Application developer / user knows needs
    - Operating system designer does not (*Howell, 1998*)

Static Previrtualization

- Application system calls partially evaluated
- Resulting code is
  - Compact
  - Efficient
  - Portable
  - Isolatable
  - Less vulnerable to attack
  - More amenable to static analysis
- LiveCD or virtual appliance, but without redundant software

Project Background

- Tried package minimization: Reduces footprint but granularity is too coarse
- Evaluated existing partial evaluation technology:
  - CMix-II (Henning Makholm)
  - Tempo (Charles Consel)
- The technology is impressive but not current with language/architecture changes (C99 or 64-bit machines)
- More recently, we switched to LLVM
- We have developed a previrtualization/monitoring toolchain called **Occam** based on LLVM
- It has been applied to web servers and PHP/MiniBlog

Reducing Functionality with **Occam**

- **Program**: `thttpd`
- **Size**: 11,322 lines
- **Problems**
  - Uses potentially dangerous functions like listen , connect, etc.
  - Reads configuration data from the command line.
- **Solutions**
  - Limit the ways that dangerous functions can be called.
  - Compile configuration data into the program.

Partial Evaluation of LLVM Bitcode

- Low Level Virtual Machine (LLVM) is a typed, machine-independent intermediate format (IF, called bitcode) due to Adve and Lattner.
- The IF uses static single assignment on typed registers.
- Many languages have front-ends to generate LLVM, e.g., Ada, C, C++, Objective C, Haskell.
- Analyzers and code-generators can be driven from LLVM.
- `glibc` could not be directly converted to bitcode, but `uClibc` was adequate for this purpose.
- Simple forms of partial evaluation on LLVM have been explored:
  - Fujita uses cloning and LLVM's optimizer
  - Smowton and Hand inline file data

Workflow

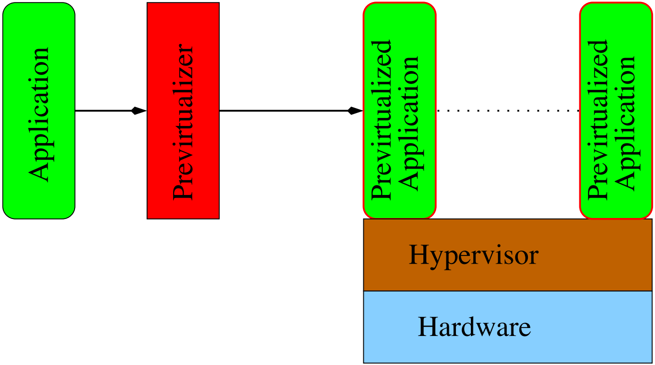
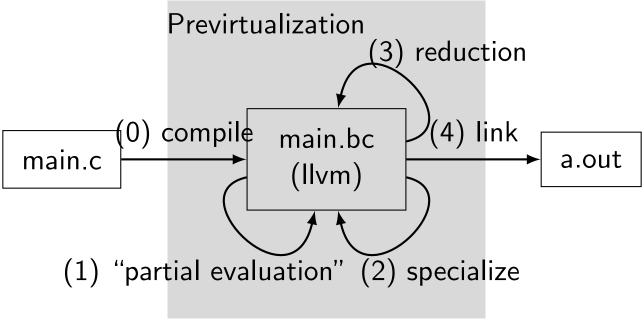


Figure 2: Previrtualizing Applications

Outline of Talk

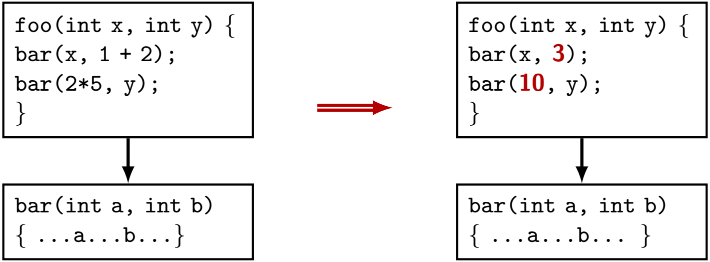
1. Reduce the “functionality” of a system
    - `nweb` is a simple webserver.
    - It doesn’t need to be able to listen on arbitrary ports.
    - Make configuration options static.
2. Overcome static analysis
    - Miniblog should never send email, so that functionality should not be in the system.
    - We need to cut it out, since mail is in the PHP standard library (compiled into the interpreter!).
3. Monitor systems and enforce dynamic policies
    - Log function calls as the program runs.
    - Check security properties.

Module Previrtualization Overview



Partial Evaluation

- Simplify the program as much as possible, want to expose constants.



```
foo(int x, int y) {
bar(x, 1 + 2);
bar(2*5, y);
}
```

```
bar(int a, int b)
{ ...a...b...}
```

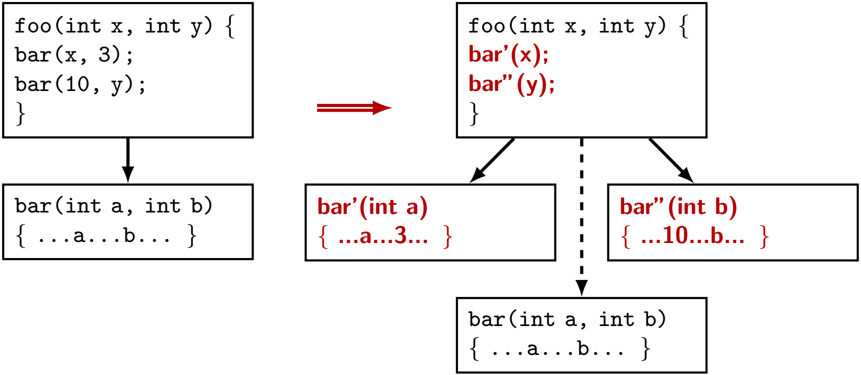
```
foo(int x, int y) {
bar(x, 3);
bar(10, y);
}
```

```
bar(int a, int b)
{ ...a...b... }
```

- Use LLVM's -O3.

Specialization

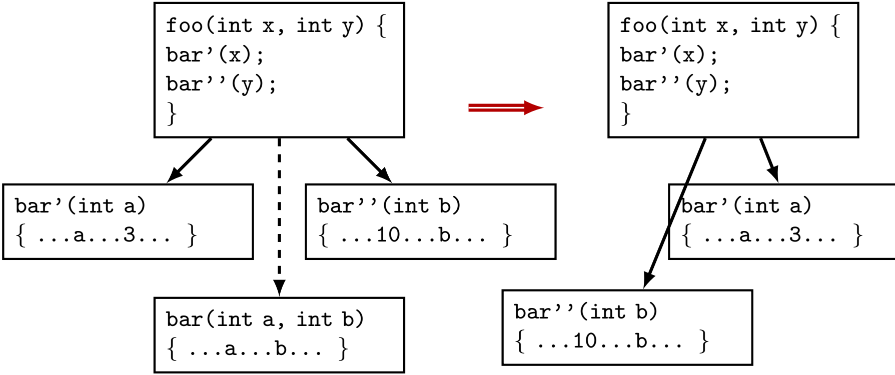
- Specialize functions when they take constant arguments.



- Clone functions and inline constants in a custom LLVM pass.

Reduction

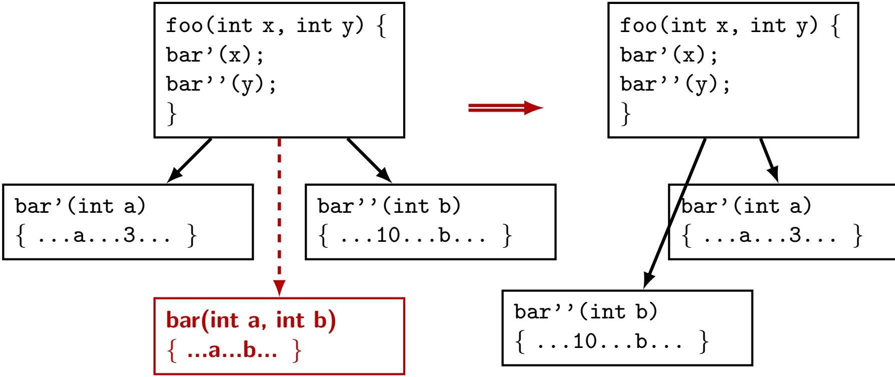
- Eliminate unused code.



- LLVM dead-code/global elimination pass.

Reduction

- Eliminate unused code.



```
foo(int x, int y) {
bar'(x);
bar''(y);
}
```

```
bar'(int a)
{ ...a...3... }
```

```
bar''(int b)
{ ...10...b... }
```

bar(int a, int b)
{ ...a...b... }

```
foo(int x, int y) {
bar'(x);
bar''(y);
}
```

```
bar'(int a)
{ ...a...3... }
```

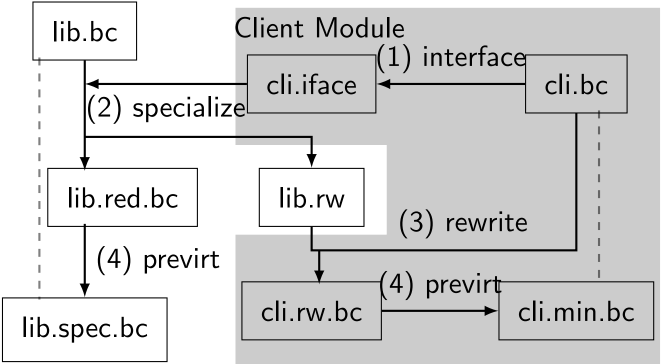
```
bar''(int b)
{ ...10...b... }
```

- LLVM dead-code/global elimination pass.

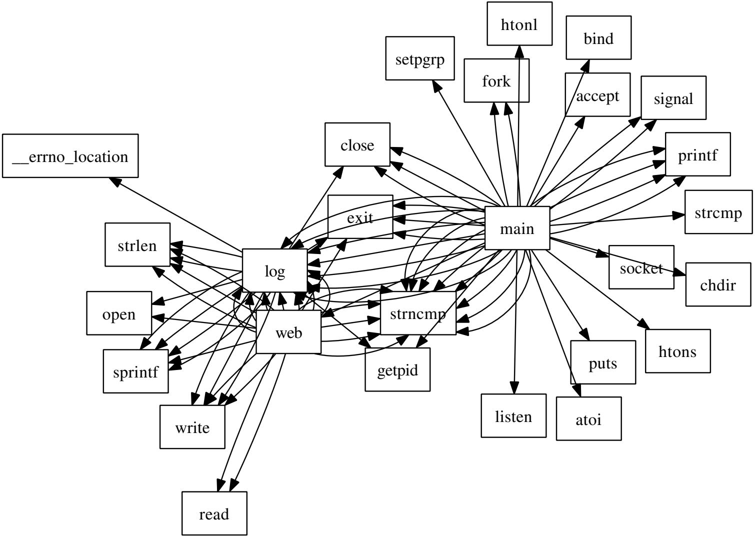
thttpd Previrtualization

1. Specialization of command line parameters
2. Partial evaluation by optimization
3. Aggressive specialization of dangerous functions
4. Dead-code elimination
5. Goto 2!

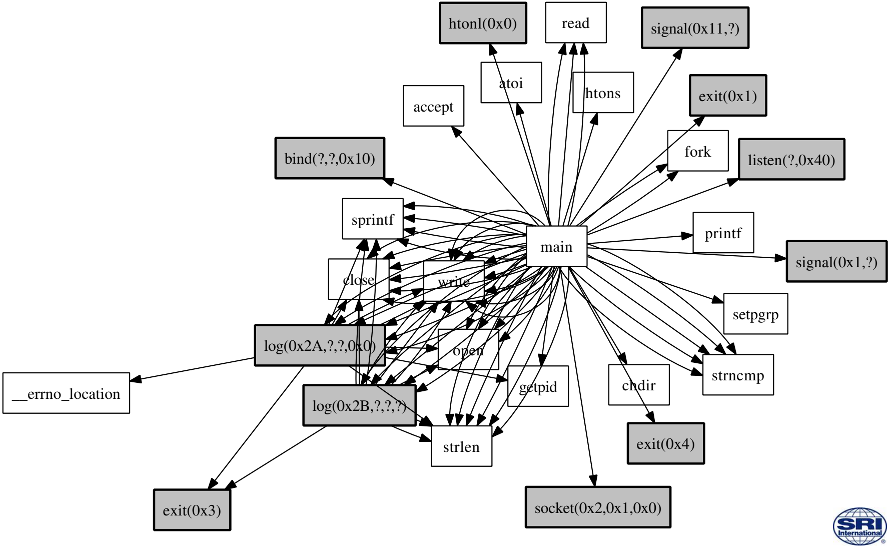
Cross-module Previrtualization



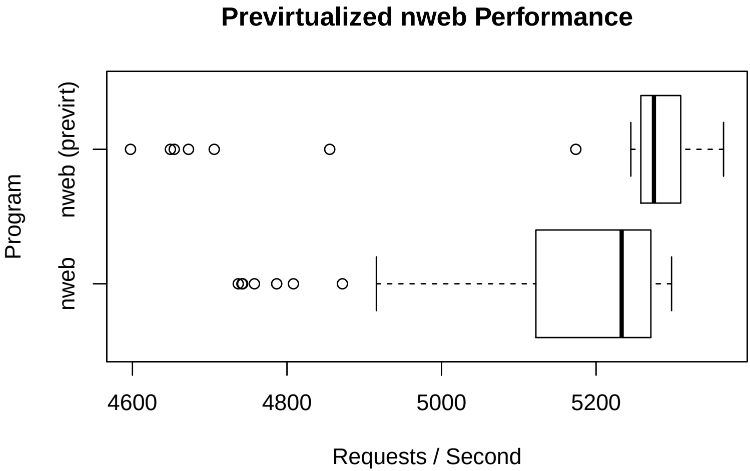
Callgraphs: Before



Callgraphs: Before & After

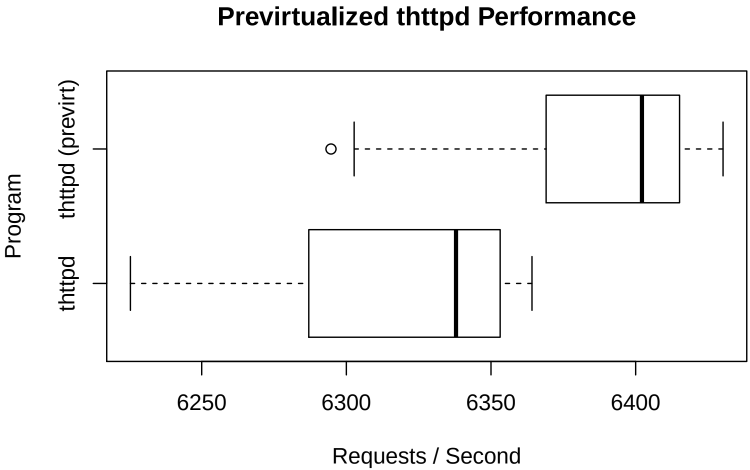


Performance of Previrtualized Software



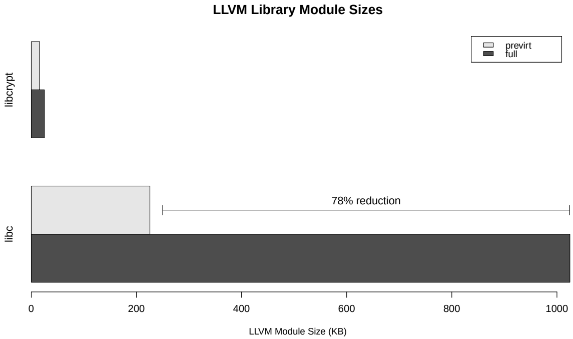
nweb performance before previrtualization.

Performance of Previrtualized Software (`thttpd`)

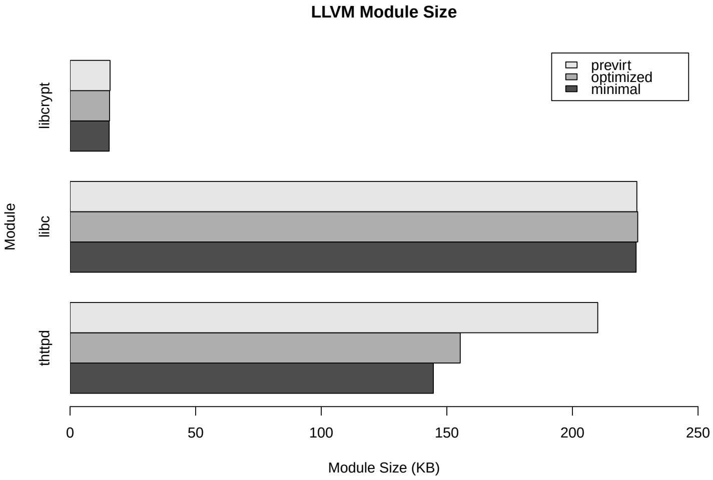


`thttpd` performance after previrtualization.

Size of Previrtualized Software



Size of Previrtualized Software



Limits of Compile-time Analysis

- We can't automatically determine reachable code in all cases
  - Cross-language or cross-binary calls
  - Indirect function calls & static approximations (PHP problem)
  - Function pointers and binary compatibility
- **PHP built-in functions are implemented as a large function table.**
  - Static analysis has to say that all of these are reachable.
  - Lets the bad in with the good.

PHP Snippet

```
const zend_function_entry basic_functions[] =
{ ... PHP_FE(system, arginfo_system) , ... };
PHP_FUNCTION(system)
{ php_exec_ex(INTERNAL_FUNCTION_PARAM_PASSTHRU, 1); }
```

Solution

1. “Statically analyze” the PHP code and determine the functions that it will call.
   - For relatively static applications this can be done with a `grep`-like static analysis.
   - Miniblog requires about 46 PHP functions out of the 1028 functions that a minimal PHP install would have.
2. Implement a transformation that will replace these unused functions with a simple exit(1).
   - Previrtualize the result to remove all the unnecessary code.

Specifying Rewrites

- We can specify subs the same way that we refer to specializations.

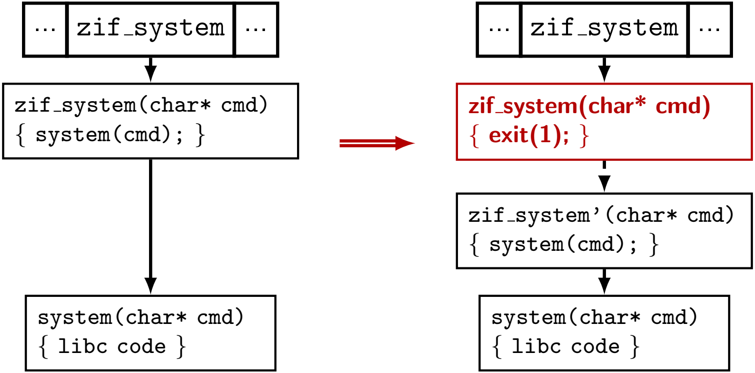
Remove `system` Function

```
zif_system(?) => fail
```

- **fail** is a keyword meaning call `exit(1)`.
- Question marks specify wildcard arguments; here we stub *all* calls to `zif_system`.
  - Also support integer constants, so we can reject some calls but not others.

Rewriting Code

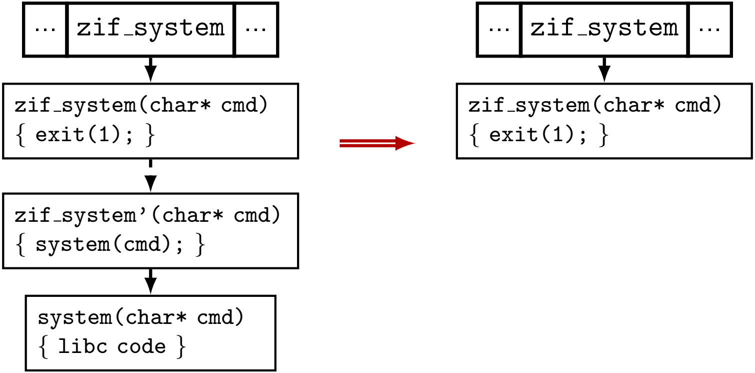
- Small transformation pass to replace function bodies.



- Implemented as a custom LLVM transformation pass.

Reusing the Previtualization Hammer

- Remove dead code using previrtualization.



```
··· zif_system ···

zif_system(char* cmd)
{ exit(1); }

zif_system'(char* cmd)
{ system(cmd); }

system(char* cmd)
{ libc code }
```

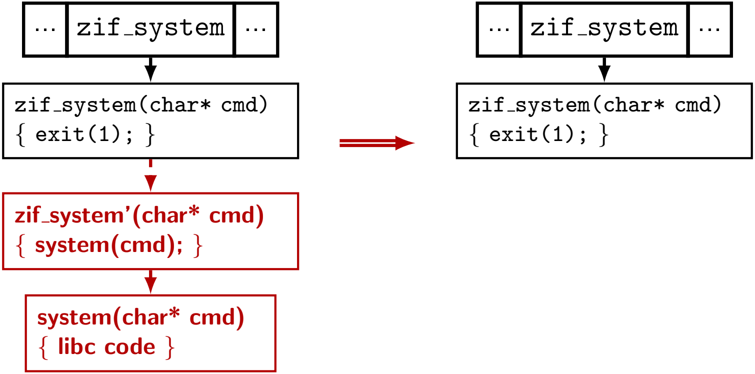
```
··· zif_system ···

zif_system(char* cmd)
{ exit(1); }
```

- Reduce to an already solved problem!

Reusing the Previrtualization Hammer

- Remove dead code using previrtualization.



- Reduce to an already solved problem!

PHP/Miniblog Previrtualization

- Remove dangerous PHP functions:
  - system
  - mail
  - etc.
- Previrtualization removes unused dependencies.

Approach

- Extend the enforcement mechanism.
- An implementation of *Aspect-Oriented Programming* for LLVM.
    - Monitor when execution enters/exits a function.
    - Support access to function arguments and return values.
    - Support conditional monitoring.
        - Allowing exit (1) on certain parameters.
    - Monitored binaries can be run *without* monitors.

Does Previrtualization Increase Security?

- Many attacks exploit buffer overflow and format string vulnerabilities to inject code or invoke existing functionality.
- Protections like *StackGuard* have a runtime cost.
- Attacks like `return-to-libc` and return-oriented programming (ROP) can be defeated by address space layout randomization (ASLR) on 64-bit machines.
- Even through previrtualization introduces more potential attack sequences for ROP, this is dwarfed by the entropy introduced by 64 bits.
- The bigger gain is that many potential vulnerabilities are pruned by previrtualization.
- Specifically, vulnerabilities in start-up code are unavailable in the previrtualized application.

Related Work

- Massalin's *Synthesis* kernel used partial evaluation for a form of run-time code generation for efficiency.
- McNamee, *et al.* optimized frequently used system calls with PE.
- Fujita exploited the LLVM optimizer for intra-module partial evaluation
- Smowton and Hand used this technique for inlining file data.
- Turnkey Linux distributes coarsely pruned appliances for several applications, including a JeOS (Just enough Operating System) stack.

Future Work

- Improve the previrtualization toolchain
- Deeper partial evaluation
- Kernel previrtualization: Compiled FreeBSD with `clang`
- Inter-application previrtualization
- Adding security checks and monitoring during previrtualization
- VM previrtualization
- Other platforms: Android
- Previrtualization as a service.

Conclusions

- **Occam** is a tool for *previrtualization*
  - Program specialization to reduce *functionality*.
  - Partial evaluation through optimization.
  - Works well for generic platforms, e.g., languages with large libraries like PHP.
- Monitoring program execution
  - Monitors can be placed around functions and modify both inputs and outputs.
  - Monitors can be arbitrary C++ code and can maintain state between calls.
  - Aspect-oriented programming
- These techniques can be used for shrinking and wrapping the software stack for each deployment