Replace your exploit-ridden firmware with a Linux kernel

Ron Minnich, Gan-shun Lim, Ryan O'Leary, Chris Koch, Xuan Chen
Google

Andrey Mirtchovski
Cisco

The problem

- Linux no longer controls the x86 platform
- Between Linux and the hardware are *at least* 2.5 kernels
- They are completely proprietary and (perhaps not surprisingly) exploit-friendly
- And the exploits can *persist*, i.e. be written to FLASH, and you can't fix that

The operating systems

Code you know about

Ring 3 (User)

Ring 0 (Linux)

Ring -1 (Xen etc.)

Code you don’t know about

Ring -2 kernel and ½ kernel
Control all CPU resources.
Invisible to Ring -1, 0, 3

SMM ½ kernel. Traps to 8086 16-bit mode.

UEFI kernel running in 64-bit paged mode.

Ring -3 kernels

Management Engine, ISH, IE.
Higher privilege than Ring -2.
Can turn on node and reimage disks invisibly. Minix 3.

X86 CPU you know about

X86 CPU(s) you don’t know about

What’s in ring -2 and ring -3?

- IP stacks (4 and 6)
- File systems
- Drivers (disk, net, USB, mouse)
- Web servers
- Passwords (yours)
- Can reimage your workstation even if it’s powered off

Ring -3 OS: ME (Management Engine)

- Full Network manageability
- Regular Network manageability
- Manageability
- Small business technology
- Level III manageability
- IntelR Anti-Theft (AT)
- IntelR Capability Licensing Service (CLS)
- IntelR Power Sharing Technology (MPC)
- ICC Over Clocking
- Protected Audio Video Path (PAVP)
- IPV6
- KVM Remote Control (KVM)
- Outbreak Containment Heuristic (OCH)
- Virtual LAN (VLAN)
- TLS
- Wireless LAN (WLAN)

ME *seems* like a good idea

- Upside: ME can recover/reimage desktops even if turned off/bricked
  - Which is also a downside
- Linux might *think* it can secure the CPU
- Just one flaw in the ME undoes all security
- Might there be more than one flaw?

Vassilios Ververis: https://goo.gl/j7Jmx5

- Great overview of many early ME flaws
- Summary: just about every part of the ME software can be attacked
- Only some of the bugs get fixed ...

‘Intel ME exploit’: 50M hits

- “Wired” headline: “HACK BRIEF: INTEL FIXES A CRITICAL BUG THAT LINGERED FOR 7 DANG YEARS”
- How many is that? One billion systems?
- Bug was in the built-in web server in the ME
    - Yep: the hidden CPU had a web server
    - That evidently you can’t turn off
    - Even though docs said you could

Ah, but *which* “critical bug”?

- If you think it’s just one, found after many years, think again
- The ME has been a rich source of exploits, many of them not widely known
- The more we look, the more we find
- “... they are only locking ¼ of the region that needs to be locked” -- https://goo.gl/3jR6WD
  - Word-length to byte-length conversion error

Ring -2 “½ OS”: System Management Mode (SMM)

- Originally used for power management
- No time for full details but …
  - Vectors to 8086 16-bit mode code
    - I.e. great place for an attack
  - All kinds of interrupts can go here, e.g. USB
  - Nowadays *almost* all of these go out again to ACPI
- That said, it’s a very nasty bit of code
- Vendors use it as secret way to “value-add”

Are there SMI exploits?

- “system management interrupt exploit” -- 630K hits
- So, yes.
- Chipsets guarantee that once SMM is installed, can’t change it, see it, turn it off
  - SMM “hidden” memory at top 8 MiB of DRAM.
- SMM maintains vendor control over … *you*

Another SMM issue: jitter

- All CPUs stop for an SMM
  - Can not be blocked
  - Can take a long time
- Makes real time very difficult
- Killed more than one product

Ring -2 OS: UEFI

- UEFI runs on the main CPU
- Extremely complex kernel
- Millions of lines of code
- UEFI applications are active after boot
- Security model is obscurity

Are there UEFI exploits?

- Absolutely
- Since UEFI (and *only* UEFI) can rewrite itself
  - These exploits can be made persistent
- You might even have UEFI fake the process of removing an exploit
- The only fix? A shredder

(Some) UEFI components

CsmVideo
Terminal
SBAHCI
AHCI
AhciSmm
BIOSBLKIO
IdeSecurity
IDESMM
CSMCORE
HeciSMM
AINT13
HECIDXE
AMITSE
DpcDxe

ArpDxe
SnpDxe
MnpDxe
UefiPxeBcDxe
NetworkStackSetupScreen
TcpDxe
Dhcp4Dxe
Ip4ConfigDxe
Ip4Dxe
Mtftp4Dxe
Udp4Dxe
Dhcp6Dxe
Ip6Dxe
Mtftp6Dxe

Udp6Dxe
IpSecDxe
UNDI
IsaBusDxe
IsaIoDxe
IsaSerialDxe
DiskIoDxe
ScsiBus
Scsidisk
GraphicsConsoleDxe
CgaClassDxe
SetupBrowser
EhciDxe
UhciDxe
UsbMassStorageDxe

UsbKbDxe
UsbMouseDxe
UsbBusDxe
XhciDxe
USB/XHCI/etc
Legacy8259
DigitalTermometerSensor (sic)

Summary

- 2 ½ hidden OSes in your Intel x86 system
- They have many capabilities
- They have network stacks and web servers
- They implement self-modifying code that can persist across power cycles and reinstalls
- They hide, have bugs, and control Linux
- Exploits have happened
- Scared yet? We sure are!

Can we fix this mess?

- Partially ...
  - Moving to AMD is not a solution, they’re closed too
  - Don’t believe all you read about Ryzen
- We focus on Intel x86 for now
- Reduce the scope of the 2 ½ OSes
- Overall project is called NERF
- Non-Extensible Reduced Firmware
  - Extensibility Considered Harmful

Non-Extensible Reduce Firmware

- Make firmware less capable of doing harm
- Make its actions more visible
- Remove all runtime components
  - Well, almost all: the ME is very hard to kill
  - But we took away its web server and IP stack
- Remove ME/UEFI self-reflash capability
- Remove UEFI IP stack and other drivers
- Linux manages flash updates

NERF components

- De-blobbed ME
- UEFI reduced to its most basic parts
- SMM disabled or vectored to Linux
- Linux kernel
- Userland written in Go (http://u-root.tk)

Removing the ME

- We don’t want it at all but that’s not an option
- If you remove ME firmware, your node
  - May never work again
  - May not power on (as in OCP nodes)
  - May power on, but will turn off in thirty minutes
- Good news: ME firmware has components
- And most are removable
  - Thanks Trammell Hudson

Removing most of the ME code

- me_cleaner can remove ME blobs
- https://github.com/corna/me_cleaner
- On minnowmax, 5M of 8M FLASH is ME
- me_cleaner.py reduces it to 300K
- Removes web server, IP stack, pretty much all the things you don’t want “Ring -3” doing
- Server (SPS) is not yet solved

Me_cleaner on the minnowmax

```
BUP                 (Uncomp., 0x045000 - 0x05a000): NOT removed, essential
KERNEL              (Uncomp., 0x05a000 - 0x08d000): removed
POLICY              (Uncomp., 0x08d000 - 0x0a8000): removed
HOSTCOMM            (Uncomp., 0x0a8000 - 0x0c0000): removed
FPF                 (Uncomp., 0x0c0000 - 0x0c6000): removed
RSA                 (LZMA   , 0x0c6000 - 0x0cc385): removed
fTPM                (LZMA   , 0x0cd000 - 0x0dc305): removed
ClsPriv             (Uncomp., 0x0dd000 - 0x0df000): removed
CLS                 (Uncomp., 0x0df000 - 0x0e8000): removed
SessMgr             (LZMA   , 0x0e8000 - 0x0f3906): removed
TDT                 (LZMA   , 0x0f4000 - 0x0f9452): removed
```

It’s an eye test on OCP ...

BUP	b2c2962872f9efb7fc905c53a56c6e47565406eefe350de7bd5ea52c4c3ef264 plain
BUP	1a24f58f9b04499cb7dcbd48155294494660f484912738cfe6bcb9a1dbfe589f plain
KERNEL	5b419f959814a4dbda06fdcaba4b84ed1a2488a2acb2de1ca2234807bba6d4fa [MATCH]
POLICY	c84a79ee14d7231bd8e967fc8660228bb4f5d75a6c516247d1435cf5d266f46f [MATCH]
HOSTCOMM	5e54d9f081aecb3957ff83ea7b6b34e5209e9ed14252457cbf751019932ea92f [MATCH]
ICCMOD	ee1a0bb460d2ea9c7e1669e85a54701c50f33013ae4c10f8dbc25fadddf82bfb [MATCH]
BASEEXT	84074ba8ba4b6dca24e086be37d8c768468b63e18d1ac5909ba1f8e1d0544f9b [MATCH]
SC	5b22b84a4ac67751a55c280ce6b69c2c9d6d649a9710031db43a14f39e4a337d [MATCH]
NM	ba2ff3a68035174080a50da2fffab21c6de16b84838c9f7159ce3ec99e0c5261 [MATCH]
DM	91cbb5777bb5c5a3c2776edf15dc35b65b6ebda2ae83d0b7ea03cb080e95ea83 [MATCH]
BUP	1a24f58f9b04499cb7dcbd48155294494660f484912738cfe6bcb9a1dbfe589f plain
KERNEL	5b419f959814a4dbda06fdcaba4b84ed1a2488a2acb2de1ca2234807bba6d4fa [MATCH]
POLICY	c84a79ee14d7231bd8e967fc8660228bb4f5d75a6c516247d1435cf5d266f46f [MATCH]
HOSTCOMM	5e54d9f081aecb3957ff83ea7b6b34e5209e9ed14252457cbf751019932ea92f [MATCH]
ICCMOD	ee1a0bb460d2ea9c7e1669e85a54701c50f33013ae4c10f8dbc25fadddf82bfb [MATCH]
BASEEXT	84074ba8ba4b6dca24e086be37d8c768468b63e18d1ac5909ba1f8e1d0544f9b [MATCH]
SC	5b22b84a4ac67751a55c280ce6b69c2c9d6d649a9710031db43a14f39e4a337d [MATCH]
NM	ba2ff3a68035174080a50da2fffab21c6de16b84838c9f7159ce3ec99e0c5261 [MATCH]
DM	91cbb5777bb5c5a3c2776edf15dc35b65b6ebda2ae83d0b7ea03cb080e95ea83 [MATCH]

Still not quite sure how to remove it on Open Compute Platform

- If we delete the usual stuff, OCP won’t power on
- It’s possible that the OCP vendor set a key into the on-chip fuses and we need that key
- Note the pattern: vendor continues to control hardware in this model

Ring -2: Dealing with SMM

- We have experimental work that directs SMM interrupts to kernel handler
- Requires that kernel run *before* SMM is installed
- Or that SMM never be installed
- Most preferred: kill it
- Second: vector to kernel

Ring -2: On to UEFI ...

- There's a huge amount of capability in UEFI
  - I.e. a great place to put exploits
- We want to remove those opportunities
- Unified Extensible Firmware Interface
  - Becomes NON-extensible

(Some) UEFI components

CsmVideo
Terminal
SBAHCI
AHCI
AhciSmm
BIOSBLKIO
IdeSecurity
IDESMM
CSMCORE
HeciSMM
AINT13
HECIDXE
AMITSE
DpcDxe

ArpDxe
SnpDxe
MnpDxe
UefiPxeBcDxe
NetworkStackSetupScreen
TcpDxe
Dhcp4Dxe
Ip4ConfigDxe
Ip4Dxe
Mtftp4Dxe
Udp4Dxe
Dhcp6Dxe
Ip6Dxe
Mtftp6Dxe

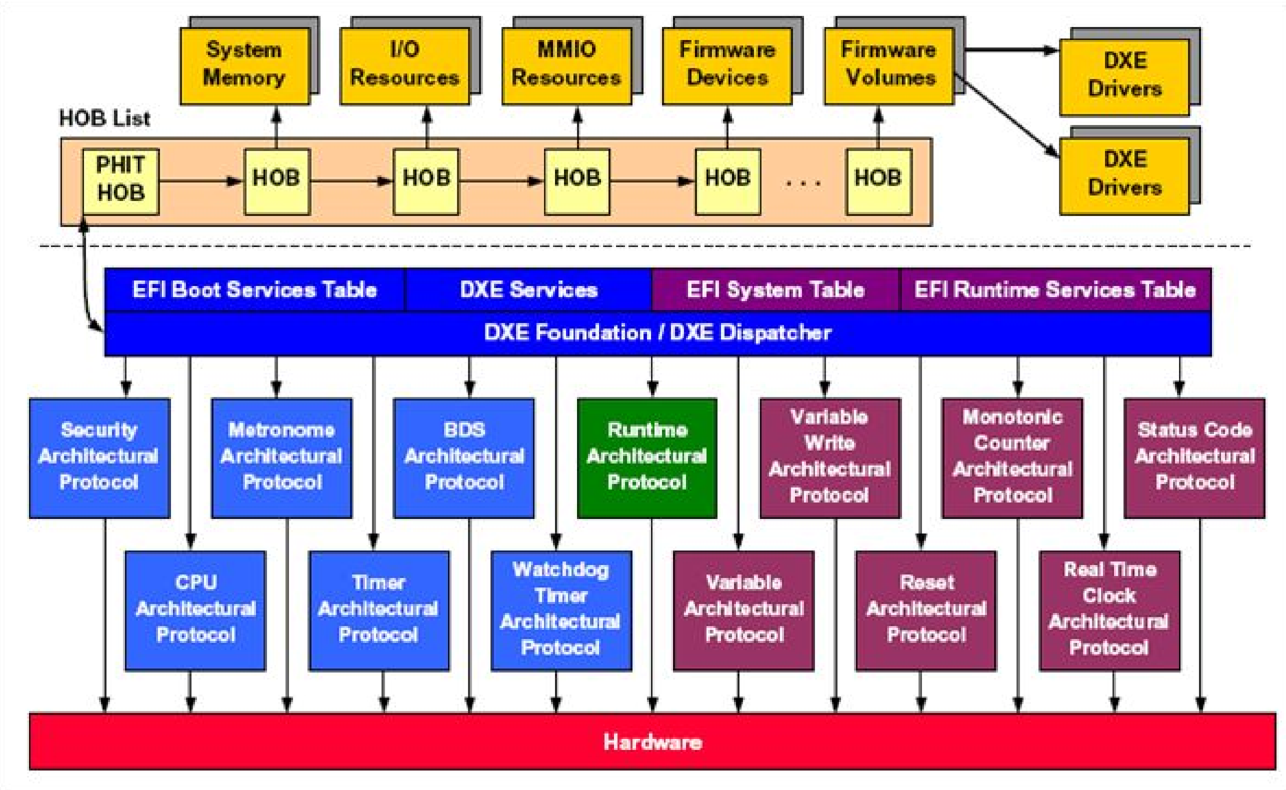
Udp6Dxe
IpSecDxe
UNDI
IsaBusDxe
IsaIoDxe
IsaSerialDxe
DiskIoDxe
ScsiBus
Scsidisk
GraphicsConsoleDxe
CgaClassDxe
SetupBrowser
EhciDxe
UhciDxe
UsbMassStorageDxe

UsbKbDxe
UsbMouseDxe
UsbBusDxe
XhciDxe
USB/XHCI/etc
Legacy8259
DigitalTermometerSensor

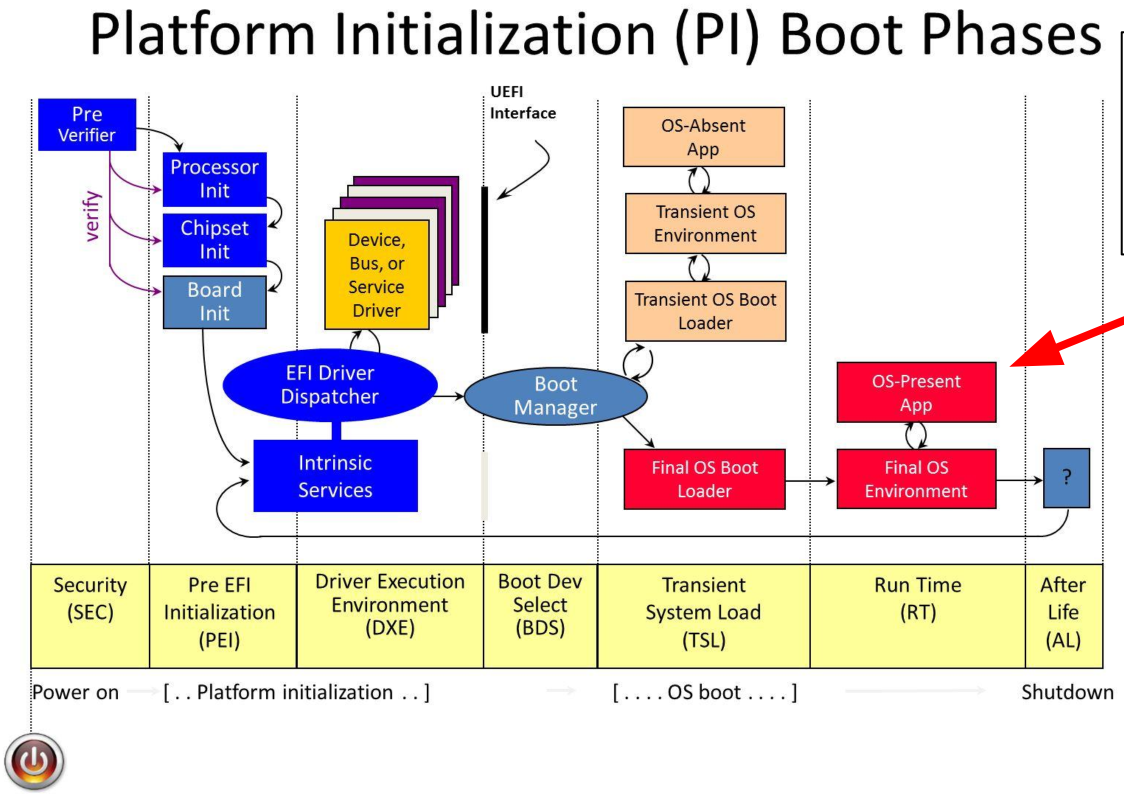
That’s a lot of stuff!

- IP stacks, USB stacks, disk drivers,
- And what does SetupBrowser do?
- We want it gone … all of it
- But what MUST we keep?
- What’s the boot process contain and what’s it look like?

UEFI Components

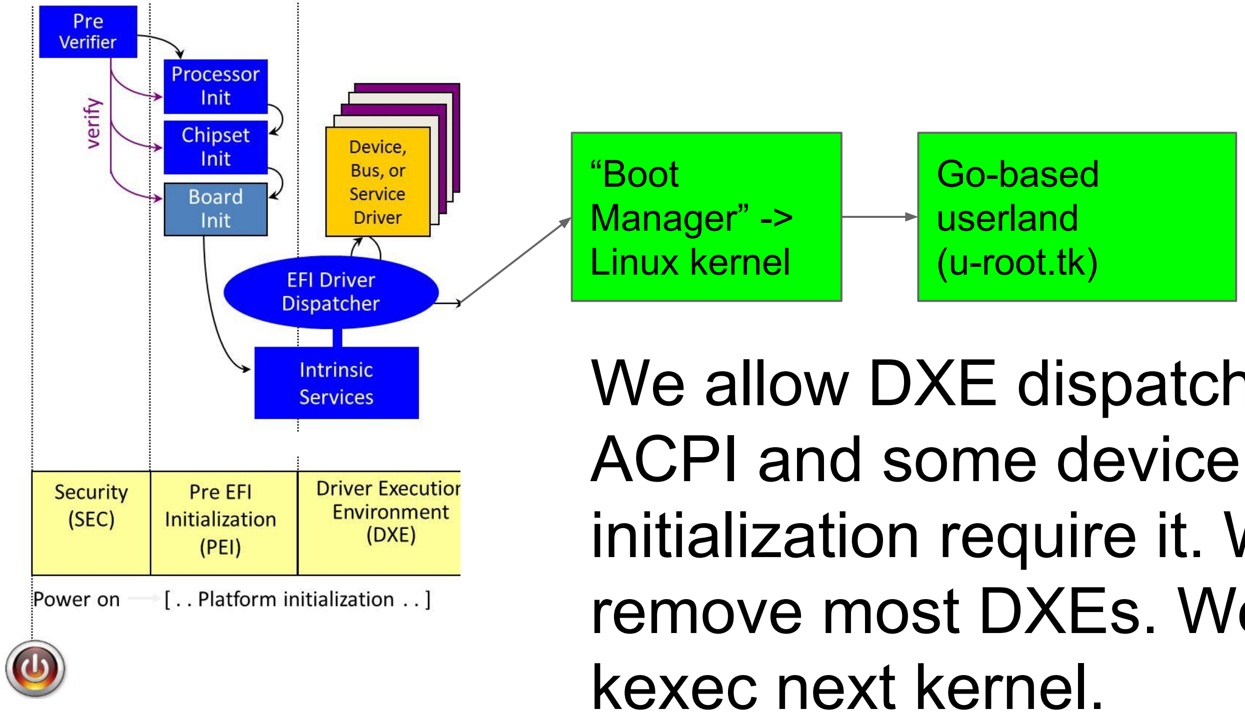


Boot steps



OS-present App, a.k.a. exploit home

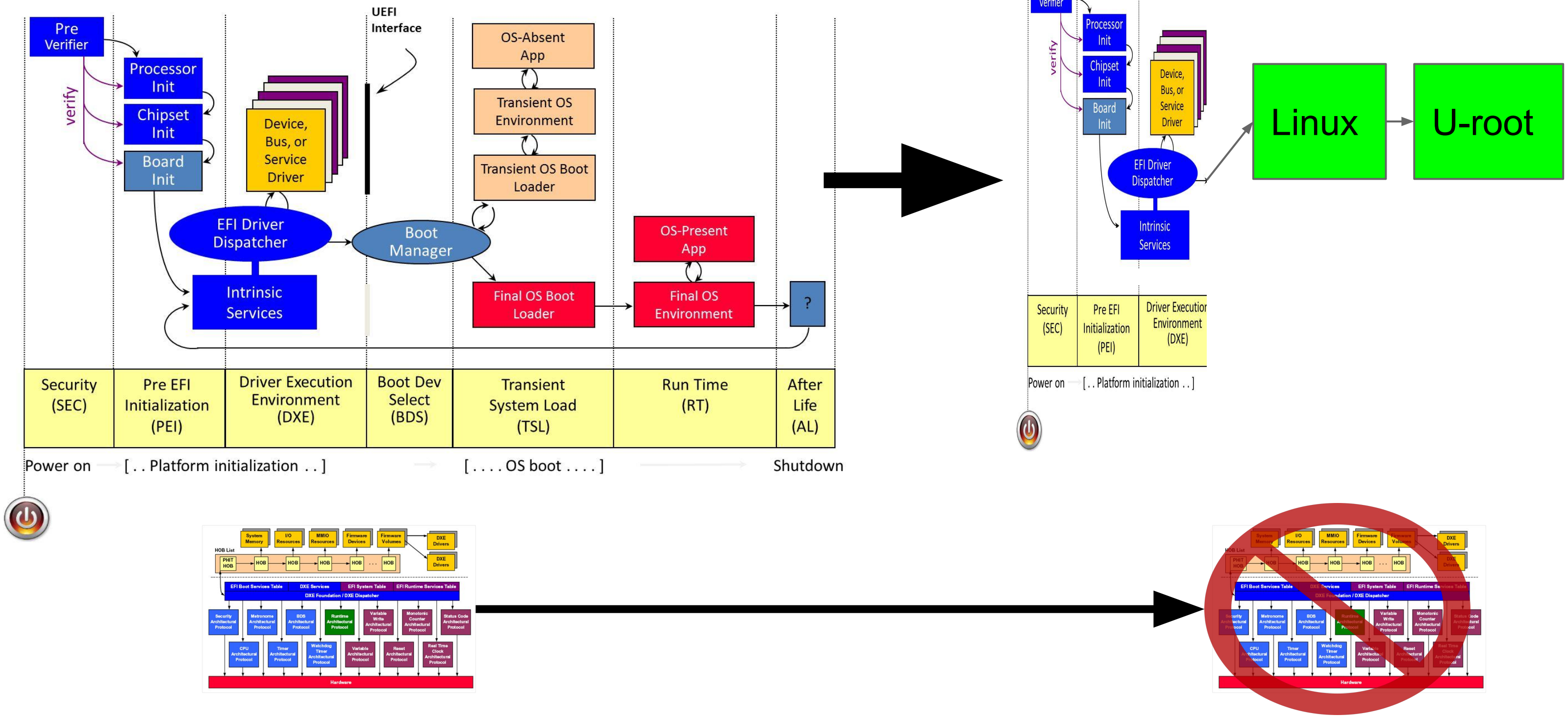
What we do instead



We allow DXE dispatcher if ACPI and some device initialization require it. We remove most DXEs. We kexec next kernel.

Net result

Platform Initialization (PI) Boot Phases



New Ring -2 kernel: Linux

- Replace UEFI DXE stage entirely with Linux
- Single kernel works on several boards
- We used to finely tune kernel for boards
  - No longer needed
- Caveat: it *is* tied to the BIOS vendor
  - Because of ACPI setup
  - Steps for AMI, TianoCore differ
- What about user space?

Userspace in Go: u-root (u-root.tk) source-based root file system

- 5.9M firmware-based initramfs that includes
  - All command source
  - All required Go compiler and package source
  - Go toolchain
- Commands compiled on first use or at boot
- About 200ms to build; 1 ms to run
- Nice from security angle since source visible
- In some cases we want only binary so ...

Can build all u-root tools into single program for compact initramfs

- File system: 1 program and many symlinks
- Use Go abstract syntax tree package to rewrite commands as packages
- Compile into one binary (takes 15s)
- Doesn’t include source code or toolchain
- Reduces footprint to 2M
- Useful when flash space is small (<5M)

Implications for startup

- Replace *all* init scripts with Go program(s)
- Do not need systemd, upstart, scripts
- Custom-built Go binary for init is very fast
- Much easier to understand than sea of scripts/unit files

Performance

- OCP boot time: 8 minutes -> 17 seconds
  - I.e. 32x speedup
  - This is to a shell prompt
- OCP boot with AMI BIOS is unreliable
  - Can’t set some boot options
  - Hangs
- Bring Linux performance and reliability to firmware

We’d love to have your help!

- Testing
- Improving Travis tests
- Porting
- Contributing
- Documenting

Extra slides for u-root

Outline

- Go in 60 seconds
- What u-root is
- How it all works
- Using Go ast package to transform Go
- Where we’re going

Go in 60 seconds

- New language from Google, released 2009
- Creators include Ken, Rob, Russ, Griesemer
- Not Object Oriented
  - By design, not ignorance
- Designed for systems programming tasks
  - And really good at that
- My main user-mode language since 2010
- Addictive

Go in 60 seconds: goo.gl/dIJrYG

```
// You can edit this code!
// Click here and start typing.
package main


import "fmt"


var a struct {
	i, j int
}
```

- Every file has a package
- Must import packages you use
- Declare ‘a’ as an anon struct

Go in 60 seconds

Could also say:

```
type b struct {
    I, j int
}
var  a b
```

- Note declarations are Pascal-style, not C style!
- “The type syntax for C is essentially unparsable.” - Rob Pike

Go in 60 seconds: goo.gl/dIJrYG

```
func init() {
	a.i = 2
}

func main() {
	b := 3
	fmt.Printf("a is %v, b is %v\n", a, b)
}
```

- init() is run before main
- You can have many init() functions
- b is declared and set
- %v figures out type

Could also say ...

fmt.Printf(“%d”, b)

Package example https://goo.gl/X2SqyZ

```
// You can edit this code!
// Click here and start typing.
package hi

var (
	internal int
	Exported int
)
```

- variables/functions starting in lowercase are not visible outside package; those starting in Uppercase are
- No export/public keyword

Package: https://goo.gl/X2SqyZ

```
func youCanNotCallFromOutside() {
    fmt.Println("hi")
}
func YouCanCallFromOutside() {
    fmt.Println("hi")
}
```

First class functions: goo.gl/pP4FcJ

```
package main

import "fmt"

var c = func(s string) {fmt.Println("hi", s)}
func main() {
	p := fmt.Println
	p("Hello, 世界")
	c(" there")
}
```

Easy concurrency: https://goo.gl/8Qt8WK

```
var done =
        make(chan int)

func x(i int) {
    fmt.Printf("%d\n", i)
    done <- 0
}

func main() {
    go x(5)
    <-done
}
```

Go in 60 seconds

- Compiler is really fast (originally based on Plan 9 C toolchain)
- V 1.2 was fastest; currently at 1.9, rewritten in Go, is still quite fast
- Compile all of u-root, including external packages, in under 15 seconds
- Package syntax makes finding all imports easy

u-root

- Go-based rootfs
  - Commands/packages written in Go
  - In one mode, MAX, compiled on demand
- 1 or 4 pre-built binaries:
  - /init
  - Go toolchain -- if compiling on demand
- Type a command, e.g. rush (shell)
  - rush and its packages are compiled to /ubin and run
  - Compilation is minimal and fast (½ second)

Key idea: $PATH drives actions

- PATH=/bin:/ubin:/buildbin
  - /bin is *usually* empty
  - /ubin is *initially* empty
- /buildbin has symlinks to an *installcommand*
- First time you type rush: found in /buildbin
  - Symlink in /buildbin: rush -> installcommand
  - Installcommand runs, builds argv[0] into /ubin
    - Execs /ubin/rush
- Next time you type rush, you run /ubin/rush

Installcommand is built on boot

- Init builds installcommand in /buildbin
- For each d in /src/github.com/u-root/u-root/cmds/*, init creates /buildbin/d -> /buildbin/installcommand
- init forks and execs rush
    - which may be compiled by the installer and run
- init: 206 lines

“U” is for “Universal”

- Single root device for all Go targets
- New architecture requires only 4 binaries
- For multi-architecture root, proper (re)arrangement of paths is needed
    - E.g., /init -> /linux_<arch>/init

Variations on u-root for embedded

- Not everyone wants source in FLASH
- Some FLASH parts are small
- Hence the root image can take many forms
- But source code never changes
  - I.e. no specialized source code for embedded

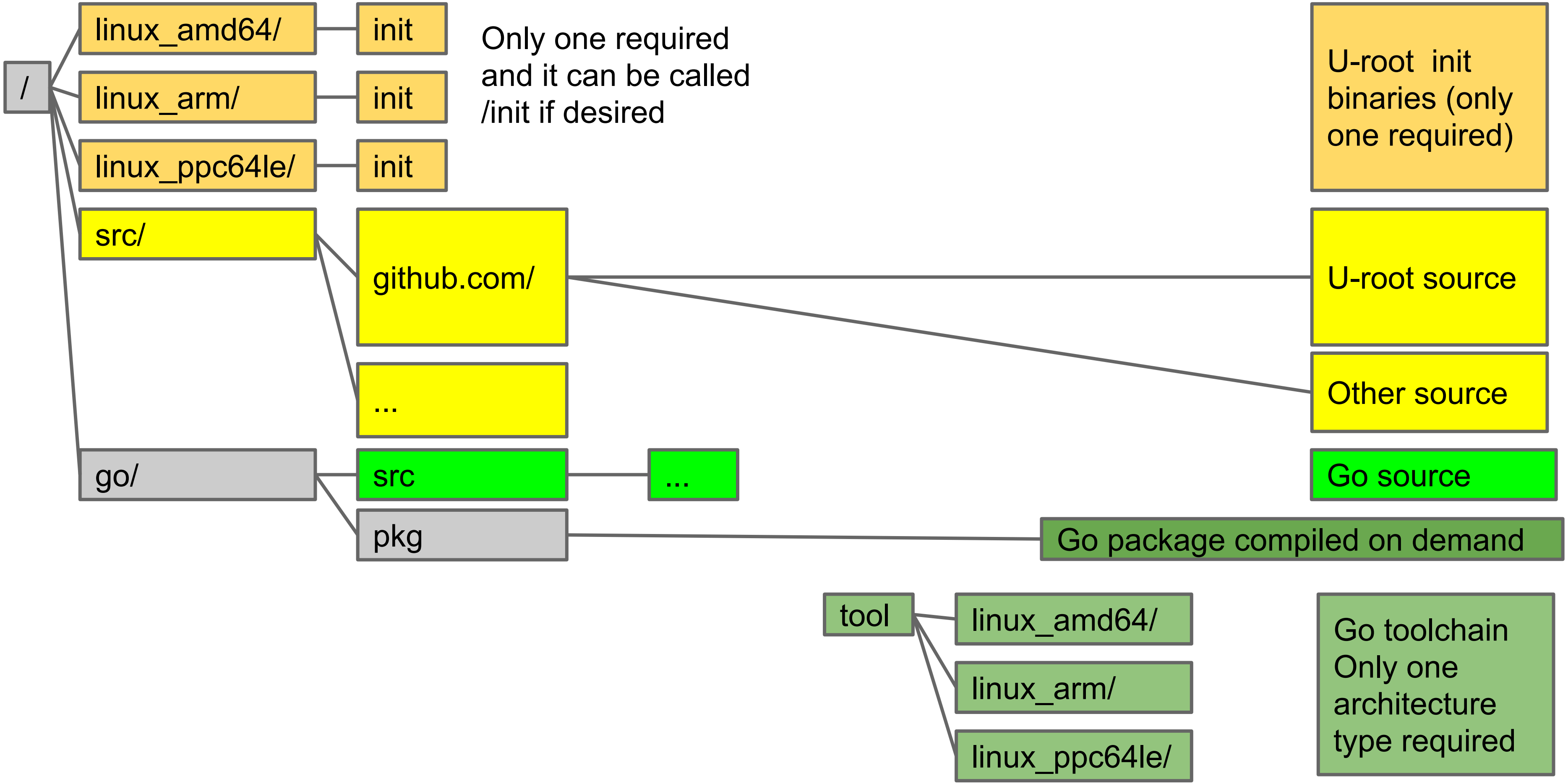
Variations of u-root

4 binaries per architecture, all commands in source form, dynamic compilation, multiple architectures in one root device	Post-boot model -- i.e. local disk, nfsroot, etc.	MAX
More than 4 binaries per architecture: some/all commands precompiled, dynamic compilation, multiple architectures in one root image	Post-boot model where faster boot is required	
4 binaries, all commands in source form, dynamic compilation, one architecture	Pre- or Post- boot model: u-root installed in firmware or local device	
All commands built into one binary which forks and execs each time	Usually firmware but also netboot of “kexec” image	MIN

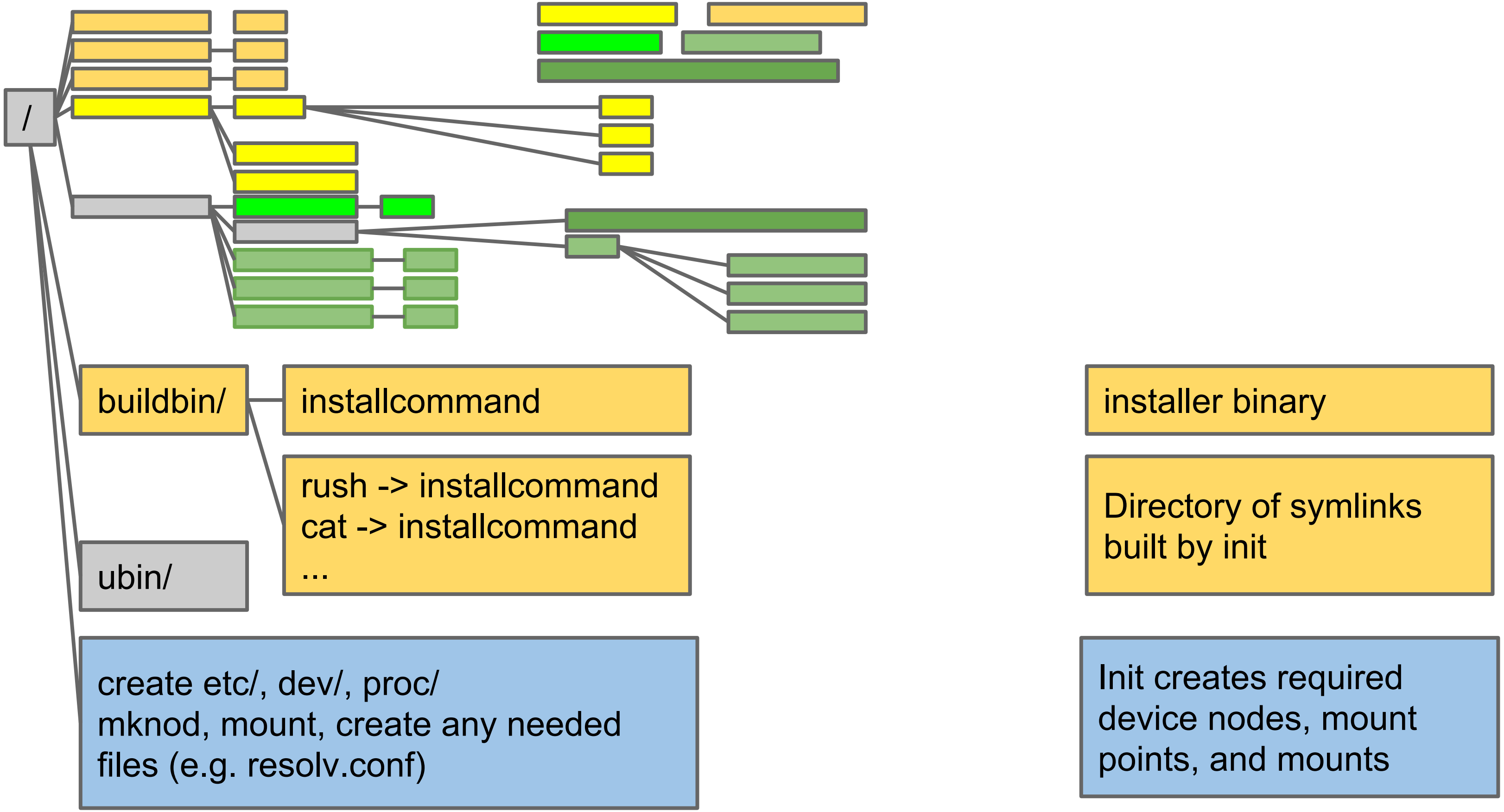
A deeper look at u-root “MAX”

- Standard kernel
- four Go binaries *per architecture**
  - init/build binary (part of u-root, written in Go)
    - Merged-in minimized go build tool
  - Compile, asm, link
- All *required* Go package **source**
- u-root source for basic commands
- in 5.9M (compressed of course! :-)

Root structure at boot



Init builds directories, mounts, ...



Init tasks

- /ubin is empty, mount tmpfs on it
- /buildbin is initialized by init with symlinks to a binary which builds commands in /bin
- PATH=/go/bin:/bin:/ubin:/buildbin
- create /dev, /proc, /etc
- Create inodes in /dev
- mount procfs
- Create minimal /etc/resolv.conv

Running first sh (rush)

- Init forks and execs rush
- If rush is not in /ubin, falls to /buildbin/rush (symlink->installcommand) runs
- /buildbin/installcommand directs go to build rush, and then execs /ubin/rush
- And you have a shell prompt
- From rush, same flow for other programs

Using Go to write more Go

- For scripting
- For dynamically creating shells with builtins
- For creating small memory pre-compiled versions of u-root (“busybox mode”)

Script for ip link command

```
run { ifaces, _ := net.Interfaces()
    for _, v := range ifaces {
        addrs, _ := v.Addrs()
        fmt.Printf("%v has %v", v, addrs)
    } }
```

- Result:

  ip: {1 1500 lo up|loopback} has [127.0.0.1/8 ::1/128]
  ip: {5 1500 eth0 fa:42:2c:d4:0e:01 up|broadcast} has [172.17.0.2/16 fe80::f842:2cff:fed4:e01/64]

- But it’s not really a program … how’s that work?

‘Run’ command rewrites fragment and uses the go import package

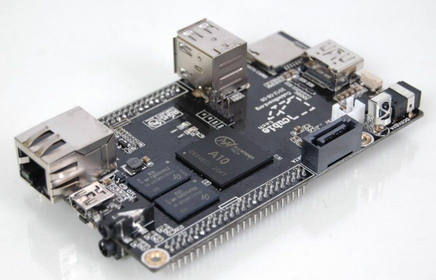
- run reads the program
  - If the first char is ‘{‘, assumes it is a fragment and wraps ‘package main’ and ‘func main()’ boiler plate
- Import uses the Go Abstract Syntax Tree (ast) package:
  - Parses a program
  - Finds package usage
  - Inserts go “import” statements

The result

- run program builds and runs the code
- Uses Go to write new Go

```
package main
import “net”
import “fmt”
func main(){
    ifaces, _ := net.Interfaces()
      for _, v := range ifaces {
            addrs, _ := v.Addrs()
            fmt.Printf("%v has %v", v, addrs)
      }
  }
```

Taking rewriting further



- Request for single-binary version of u-root for Cubieboard
  - Allwinner A10 --> not very fast
- Wanted to compile all u-root programs into one program

Taking rewriting further

- With the ast package, we can rewrite programs as packages, e.g. ls.go

```
package main

var x = flag.String("l", …)
func init() {...}
func main() {
}
```

```
package ls

var x = flag.String("ls.l", …)
func Init() {...}
func Main() {
}
```

- Combine all of u-root into one program
- Turning 65 programs into one: 10 seconds

What is all this good for?

- Building safer startup environments
- We can verify the root file system as in ChromeOS, which means we verify the compiler and source, so we know what we're running
- Much easier embedded root
- Security that comes from source-based root
- Knowing how things work

But I want bash!

- It's ok!: tinycorelinux.net has it
- The tcz command installs tinycore packages
- tcz [-h host] [-p port] [-a arch] [-v version]
    - Defaults to tinycore repo, port 8080, x86_64, 5.1
- Type, e.g., tcz bash
- Will fetch bash and all its dependencies
- Once done, you type
- /usr/local/bin/bash (can be in persistent disk)

Where to get it

github.com/u-root/u-root

Instructions on

U-root.tk

Status

- Demonstrated on 4 motherboards
- Hope to have a single Go tool to do the job in a few months
- Looking for collaborators
- While we prefer coreboot-based systems we can use u-root on UEFI-based systems via NERF

Basic builtin(s)

```
builtin \
  hi '{ fmt.Printf("hi\n") }' \
  there '{fmt.Println("there")}'
```

- Create a new shell with hi and there commands

Builtins combine script and rebuild

```go
package main

import "errors"
import "os"

func init() {
	addBuiltIn("cd", cd)
}

func cd(cmd string, s []string) error {
	if len(s) != 1 {
		return errors.New("usage: cd one-path")
	}
	err := os.Chdir(s[0])
	return err
}
```

- This is the ‘cd’ builtin
- Lives in /src/sh
- When sh is built, it is extended with this builtin
- Create custom shells with built-ins that are Go code
- e.g. temporarily create purpose-built shell for init
- Eliminates init boiler-plate scripts

Customize the shell in a few steps

- create a unique tempdir
- copy shell source to it
- convert sets of Go fragments to the form in previous slide
- Create private name space with new /ubin
- mount --bind the tempdir over /src/cmds/rush/ and runs /ubin/rush
- You now have a new shell with a new builtin

The new shell

- Child shells will get the builtin
  - since they inherit the private name space
- Shells outside the private name space won’t see the new shell
- When first shell and kids exit, builtin is gone
- Custom builtins are far more efficient
  - Need a special purpose shell many times?
  - You can pay the cost once, not once per exec