Secure Boot from A to Z

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embedded Linux and kernel engineering

Speakers presentation

- Embedded Linux engineers at Bootlin
  - Embedded Linux **expertise**
  - **Development**, consulting and training
  - Strong open-source focus
- Implemented full chain-of-trust on custom i.MX6 board
- Open-source contributors
- Living in **Toulouse**, south west of France

Disclaimer

- definitely **not** security experts
- presenting only one way to verify boot on a board based on a specific family of SoCs (though most parts can be applied to other boards)

Introduction

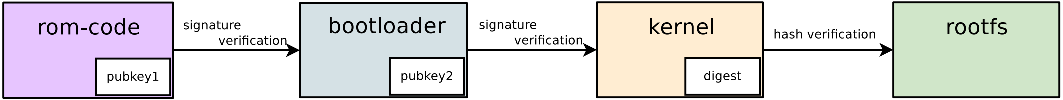
Who wants to verify the boot sequence and why?

- product vendors
  - make sure your devices are used the way they should be
  - not for a different purpose
  - not for running unapproved software (e.g. software limitations removed)
  - protect your consumers
- end users
  - make sure your system hasn't been tampered with
- basically, to make sure the binaries you're trying to load/boot/execute were built by a trustworthy person

How does it work?

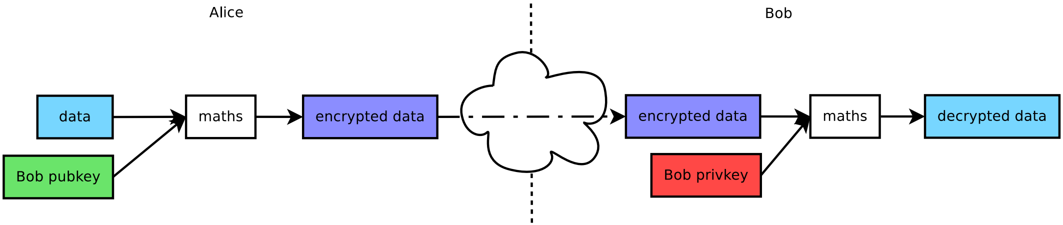
- everything is based on digital signature verification ($\neq$ encryption)
- the first element in the boot process authenticates the second, the second the third, etc...
- called a chain-of-trust: if any element is authenticated but not sufficiently locked-down (e.g. console access in bootloader, root access in userspace), the device is not verified anymore

What does a chain-of-trust look like?



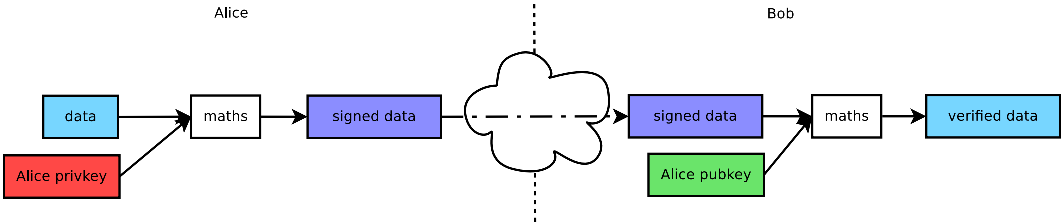
- every component is verified using its digital signature and a public key
- the rootfs integrity is verified using a hash mechanism
- our experience:
  - implemented chain-of-trust on custom i.MX6 boards
  - Quentin worked on the chain-of-trust from ROM code up to the kernel
  - Mylène worked on the root FS part of the chain-of-trust

Mandatory Alice and Bob example: encryption



- provided Bob's public key is publicly available **anyone** (Alice, Charles, David, etc.) can send **encrypted data** to someone (Bob) that is the **only one** able to decrypt it

Mandatory Alice and Bob example: signature



- provided Alice's public key is publicly available, **anyone** (Bob, Charles, David, etc.) can verify that the **signed data** someone sent them is sent by the **only one** (Alice) able to sign it

Not inconsequential

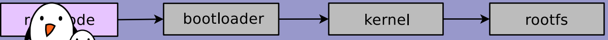
- costly in terms of:
  - logistic and overall project complexity: whole architecture to create keys, build with the keys, ...
  - workflow complexity for developers: if the platform is locked down, need to re-sign the binary every time and validate the chain-of-trust
  - boot time (bunch of authentications to be made along the way to Linux prompt)
- you have to be extremely careful with your chain-of-trust and private keys so that none is broken or leaked

ROM code - Root of trust

Specific to the SoC

rom-code → bootloader → kernel → rootfs

- need a way to store the public key(s) which will be used to decrypt the signature of the bootloader and make them tamper-proof
- each vendor can decide whatever medium they want to use to store the public keys
- microcode in charge of checking the signature is embedded in the ROM code
- different vendors: Xilinx, Tegra, Atmel, Freescale/NXP, Rockchip, ST, Samsung, ...



- the public key has to be stored on an non-volatile memory (NVM) accessible to the ROM code
- One-Time-Programmable (OTP) fuses are blown
- OTP fuses are silicon-expensive in terms of occupied area and store a relatively small amount of information
- a public key is at least 1 KiB
- less expensive to store only the hash of the public key in OTP, then compare it to the hash of the public key embedded in a given binary
- good idea to have multiple public keys so that if one private key is stolen/leaked/lost, we revoke it and we can use others and:
    1. not having a totally unverified device
    2. not having to brick the device

Secure boot sequence

rom-code → bootloader → kernel → rootfs

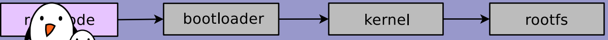
ROM code:

- loads the bootloader in a secure space to avoid physical attacks
- loads the embedded public key
- checks the hash of the public key against the hash table in the OTP
- uses this verified public key to check the signature of the bootloader
- executes the bootloader binary
- called High Assurance Boot (HAB) for this SoC family

Preparing the board

rom-code → bootloader → kernel → rootfs

- create the keys using NXP custom tool (Code Signing Tool)
- flash fuses from working unverified U-Boot using NXP-specific code and the fuse table returned by CST
- sign the bootloader using one of the keys whose hash is in the fuse table, using CST
- check status of bootloader `hab_status` which is NXP specific
- lock down bootloader loading by blowing the locking fuse

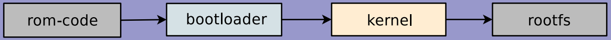



```
=> hab_status
Secure boot disabled

HAB Configuration: 0xf0, HAB State: 0x66

--------- HAB Event 1 -----------------
event data:
    0xdb 0x00 0x08 0x41 0x33 0x11 0xcf 0x00

STS = HAB_FAILURE (0x33)
RSN = HAB_INV_CSF (0x11)
CTX = HAB_CTX_CSF (0xCF)
ENG = HAB_ENG_ANY (0x00)

--------- HAB Event 2 -----------------
event data:
[...]
```

```
=> hab_status
Secure boot disabled

HAB Configuration: 0xf0, HAB State: 0x66
No HAB Events Found!
```

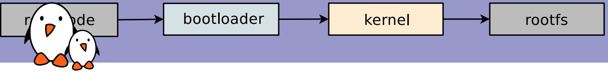
Bootloader & kernel

Trust (almost) no one



- no point of having a secure bootloader if not authenticated by ROM code
- bootloader **has** to be sufficiently locked-down, otherwise there is no point authenticating it
- specific case of U-Boot mainline: **has** to be inaccessible by anyone (no console at all: `gd->flags |= GD_FLG_DISABLE_CONSOLE` in `board_early_init_f()`)
- under no circumstances should you trust anything that isn't in the U-Boot binary that is authenticated by the ROM code
- by default, the environment can be trusted **only** if it's in the U-Boot binary (`ENV_IS_NOWHERE`)
- pending patch in U-Boot to load only a handful of variables from another environment, limiting the attack vector
  https://patchwork.ozlabs.org/patch/855542/

Kernel and DTB authentication



- U-Boot has DeviceTree Blob (DTB) support, used the same way the kernel does to probe drivers: according to the DT definition
- DTB can also be used to store a public key
- DTB is appended to the U-Boot binary and is thus affected by the computation of the hash used by the ROM code to authenticate the bootloader => can be trusted
- fitImage to have only one file containing binaries and signatures instead of lots of images to load
- `mkimage` (the tool to compile fitImages) has built-in support for signing of binaries hash

Key generation

- `openssl genrsa -out my_key.key 4096`
- `openssl req -batch -new -x509 -key my_key.key -out my_key.crt`
- `mkimage` requires certificate and private key files to be named the same

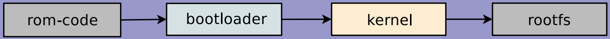
DTB creation

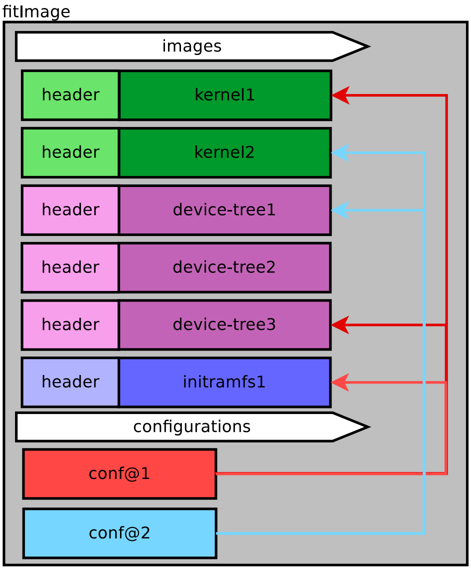
u-boot_pubkey.dts

```
/dts-v1/;
/ {
    model = "Keys";
    compatible = "vendor,board";
    signature {
        key-my_key {
          required = "image";
          algo = "sha1,rsa4096";
          key-name-hint = "my_key";
        };
    };
};
```

- `key-name-hint` and the suffix to the `key-` DT node has to be the same name as the one given to the key
- `required` is either `image` or `conf`, refer to `doc/uImage.FIT/signature.txt`

What's a fitImage?





- several talks given to present the fitImage, the reasons behind and the challenges
- it's basically a container for multiple binaries with hashing and signature support
- it also supports forcing a few binaries to be loaded together,
- supports different architectures, OSes, image types, ... => can be found in `common/image.c`

fitImage.its


```
/ {
    description = "fitImage for Foo revA and revB";
    #address-cells = <1>;
    images {
        kernel@1 {
            description = "Linux kernel";
            data = /incbin/("zImage");
            type = "kernel";
            arch = "arm";
            os = "linux";
            compression = "none";
            load = <0x10008000>;
            entry = <0x10008000>;
            signature@1 {
                algo = "sha1,rsa4096";
                key-name-hint = "my_key";
            };
        };
        fdt@1 {
            description = "DTB for Foo revA";
            data = /incbin/("foo-reva.dtb");
            type = "flat_dt";
            arch = "arm";
            compression = "none";
            signature@1 {
                algo = "sha1,rsa4096";
                key-name-hint = "my_key";
            };
        };
        fdt@2 {
            description = "DTB for Foo revB";
            data = /incbin/("foo-revb.dtb");
            type = "flat_dt";
            arch = "arm";
            compression = "none";
            signature@1 {
                algo = "sha1,rsa4096";
                key-name-hint = "my_key";
            };
        };
    };
    configurations {
        default = "conf@1";
        conf@1 {
            kernel = "kernel@1";
            fdt = "fdt@1";
        };
        conf@2 {
            kernel = "kernel@1";
            fdt = "fdt@2";
        };
    };
};
```

U-Boot & fitImage creation

rom-code → bootloader → kernel → rootfs

```
#DTB compiled out-of-tree because we need to add the public key with \code{mkimage}
dtc u-boot_pubkey.dts -O dtb -o u-boot_pubkey.dtb
make CROSS_COMPILE=arm-linux-gnueabihf- foo_defconfig
make CROSS_COMPILE=arm-linux-gnueabihf- tools
tools/mkimage -f fitImage.its -K u-boot_pubkey.dtb -k /path/to/keys -r fitImage
make CROSS_COMPILE=arm-linux-gnueabihf- EXT_DTB=u-boot_pubkey.dtb
```

U-Boot required options

rom-code → bootloader → kernel → rootfs

- `CONFIG_SECURE_BOOT=y` (specific to NXP)
- `#ifdef CONFIG_SECURE_BOOT`
  `CSF CONFIG_CSF_SIZE`
  `#endif`, at the beginning of the DCD file of your NXP board
- `CONFIG_OF_CONTROL=y`
- `CONFIG_DM=y`, `CONFIG_FIT=y`, `CONFIG_FIT_SIGNATURE=y`

fitImage booting

with a fitImage loaded @ 0x15000000:

```
=> bootm 0x15000000 #or bootm 0x15000000#conf@1 since conf@1 is the default
## Loading kernel from FIT Image at 15000000 ...
   Using 'conf@1' configuration
   Verifying Hash Integrity ... OK
   Trying 'kernel@1' kernel subimage
     Description:  Linux kernel
     Type:         Kernel Image
     Compression:  uncompressed
     Data Start:   0x150000e4
     Data Size:    7010496 Bytes = 6.7 MiB
     Architecture: ARM
     OS:           Linux
     Load Address: 0x10008000
     Entry Point:  0x10008000
     Hash algo:    sha1
     Hash value:   7d1fb52f2b8d1a98d555e01bc34d11550304fc26
     Sign algo:    sha1,rsa4096:my_key
     Sign value:   [redacted]
   Verifying Hash Integrity ... sha1,rsa4096:my_key+ sha1+ OK
## Loading fdt from FIT Image at 15000000 ...
   Using 'conf@1' configuration
   Trying 'fdt@1' fdt subimage
   [...]
   Verifying Hash Integrity ... sha1,rsa4096:my_key+ sha1+ OK
   Booting using the fdt blob at 0x156afd40
   Loading Kernel Image ... OK
   Loading Device Tree to 1fff2000, end 1ffff1ed ... OK

Starting kernel...
```

fitImage booting

with a fitImage loaded @ 0x15000000:

```
=> bootm 0x15000000 #or bootm 0x15000000#conf@1 since conf@1 is the default
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   Verifying Hash Integrity ... OK
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     Hash algo:    sha1
     Hash value:   7d1fb52f2b8d1a98d555e01bc34d11550304fc26
     Sign algo:    sha1,rsa4096:my_key
     Sign value:   [redacted]
   Verifying Hash Integrity ... sha1,rsa4096:my_key+ sha1+ OK
## Loading fdt from FIT Image at 15000000 ...
   Using 'conf@1' configuration
   Trying 'fdt@1' fdt subimage
   Verifying Hash Integrity ... sha1,rsa4096:my_key- Failed to verify required signature 'key-my_key'
 error!
Unable to verify required signature for '' hash node in 'fdt@1' image node
Bad Data Hash
   Booting using the fdt blob at 0x156ba280
   Loading Kernel Image ... OK
ERROR: image is not a fdt - must RESET the board to recover.
FDT creation failed! hanging...### ERROR ### Please RESET the board ###
```

Root filesystem

The chosen solutions

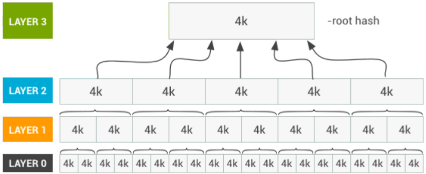
rom-code → bootloader → kernel → rootfs

To have a verified root filesystem, we have chosen the following solutions:

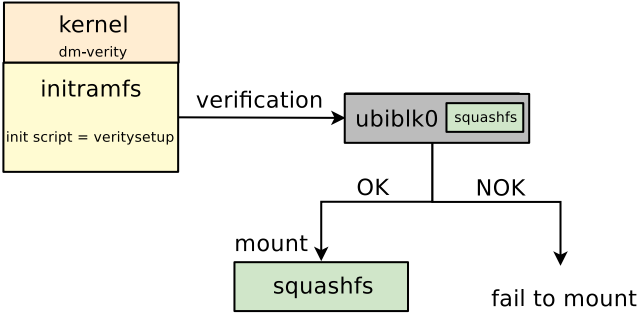
- Have an unalterable filesystem:
  - read-only filesystem: impossible to modify it
    => `squashfs`: type for read-only filesystem
  - Not part of the secure-boot process but it was important for us
- Authenticate the rootfs
  - `dm-verity`:
    - infrastructure to check if the rootfs is the one we are expecting
      => authentication of the squashfs image
    - needs userspace applications to authenticate the system. Need to have these tools available
      => use an initramfs builtin as a first filesystem
    - the kernel is already in the chain of trust

dm-verity

- `Device-Mapper`: infrastructure in the Linux kernel to create virtual layers of block devices
- `Device-Mapper verity`: provides integrity checking of block devices using kernel crypto API
- could hash the whole block device and compare it with the expected hash
- instead, use a cryptographic hash tree (Merkle tree)
- blocks are hashed and hash verified with hash tree **only on access**
- except the leaf nodes that are data, each node is the hash of its children. Until only one last hash => **root hash**
- needs userspace apps: **cryptsetup** provides different tools (*veritysetup*)

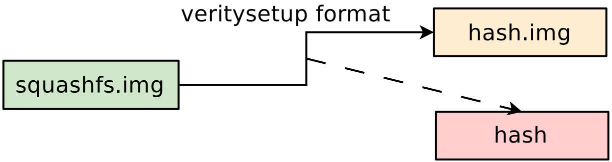


dm-verity in our case



- boot the kernel with initramfs
- have an init-script that uses `veritysetup` on block device (ubiblk0)
- `veritysetup`: a userspace application to authenticate devices according to root_hash
- if OK, verified squashfs available
- if NOK, fails to have squashfs => init stops here

dm-verity: create hash tree

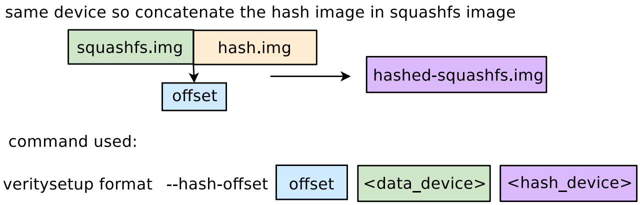


command used:

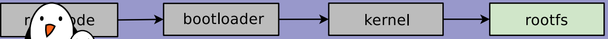
veritysetup format <data_device> <hash_device>

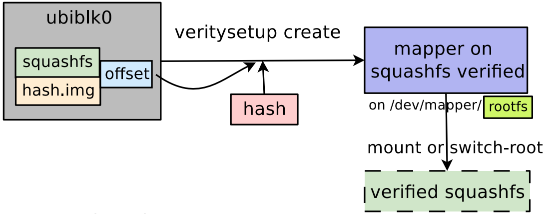
- `veritysetup` creates the hash tree (hash.img) and prints the root hash
- by default, the hash image is contained on another device/image than the one we want to authenticate

dm-verity: create hash tree



- not our use-case: want only one device
  => concatenate the hash image at the end of our squashfs image
- `veritysetup` has an option `--hash-offset` to locate the hash area in the same device/image

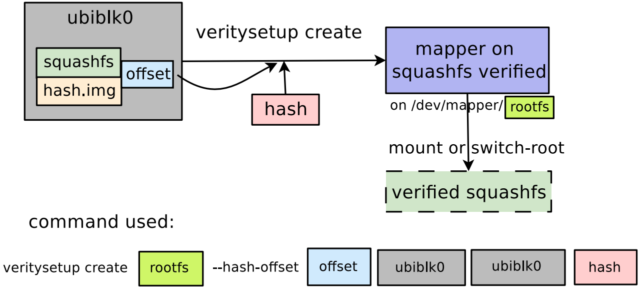




command used:

veritysetup create <name> --hash-offset <offset> <data_dev> <hash_dev> <hash>

- use `veritysetup` to authenticate the block device
- need the root hash and the offset (where to find the hash tree)
- if authentication is successful, can mount (or switch-root) the verified squashfs



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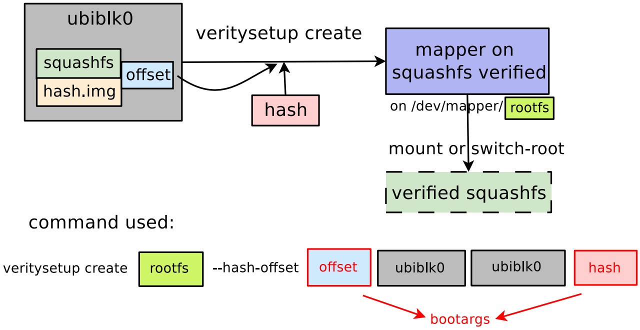

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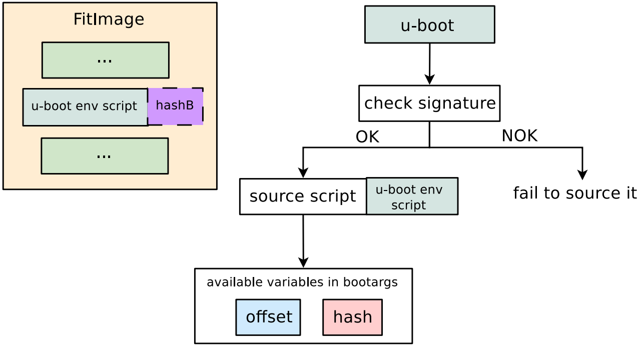
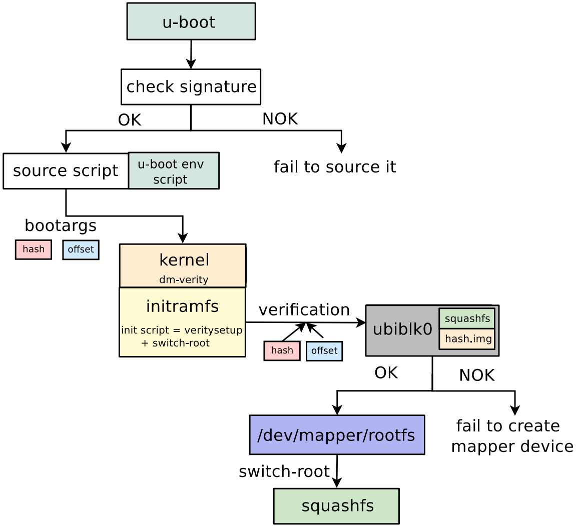
U-Boot: passing hash-offset



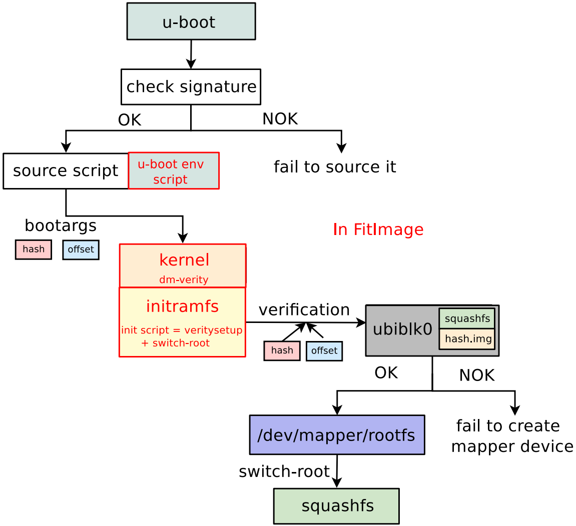
- create a U-Boot environment script
- but the U-Boot environment script can be attacked
- add this script in the `FitImage`
  => has a signature of the hash of the binary
- Once sourced, set `bootargs` to have offset and root hash

The final mechanism



- source U-Boot script to set bootargs with hash and offset
- bootargs read by Linux's init-script to retrieve hash/offset values
- used with `veritysetup` to authenticate the block device
- use `switch-root` tool to switch the rootfs from initramfs to squashfs

The final mechanism



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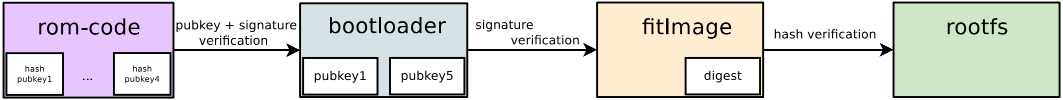
Conclusion

Chain-of-trust completed



Painful integration into Yocto

- currently, to create a fitImage, the kernel recipe is required to inherit `kernel-fitimage` class
- it's done before the rootfs is created (because usually people want the kernel to be in `/boot`)
- U-Boot script needs to be in the fitImage
- U-Boot script has to be created after the squashfs rootfs to retrieve the root hash
- and that's how you end up with a dependency loop in Yocto :)
- wrote a new image and class to work around this issue

Read-Write filesystems

- our use case was very specific: read-only root filesystem, but one might want a read-write filesystem
- if not critical (depends on your use case, e.g. logs, user data, etc...), mount it along side your read-only authenticated rootfs
- if critical, have a look at IMA/EVM
  - `http://kernsec.org/files/lss2015/ima-applications-slides.pdf`
  - `https://lwn.net/Articles/488906/`

Remember about trusting no-one?

- secure boot vulnerabilities in ROM code of i.MX6, i.MX50, i.MX53, i.MX7, i.MX28 and Vybrid families publicly disclosed July 17th, 2017
  - `https://community.nxp.com/docs/DOC-334996`
- Know your threat model, nothing is 100% secure,
  - Tutorial: Introduction to Reverse Engineering by Mike Anderson

Questions? Suggestions? Comments?

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`https://bootlin.com/pub/conferences/2018/elc/josserand-schulz-secure-boot`