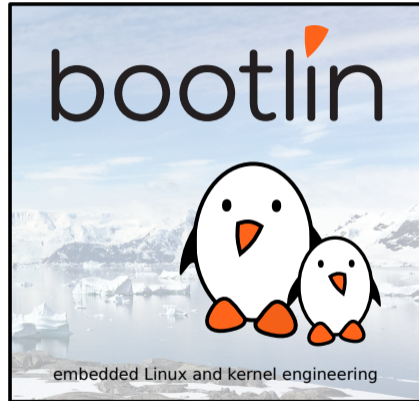




Secure boot in embedded Linux systems

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Corrections, suggestions, contributions and translations are welcome!





Who is speaking ?

- ▶ Thomas Perrot
- ▶ Embedded Linux and kernel engineer at Bootlin
- ▶ Joined in 2020
- ▶ Embedded Linux engineer and trainer
- ▶ Open-source contributor
- ▶ Based in Toulouse, France





Agenda

- ▶ Introduction
 - ▶ What is it for?
 - ▶ Chain of trust
 - ▶ Signature process
 - ▶ Workflows impacts
- ▶ Presenting one of available solutions based on:
 - ▶ NXP i.MX8 AHAB secure boot
 - ▶ U-boot verified boot
 - ▶ dm-init + dm-verity



Introduction

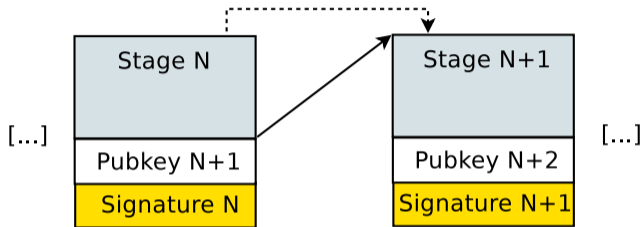


What is it for?

- ▶ system integrity checking at boot
- ▶ prevent
 - ▶ hijack
 - ▶ tampering
 - ▶ unauthorized software
 - ▶ malware execution



Chain of trust

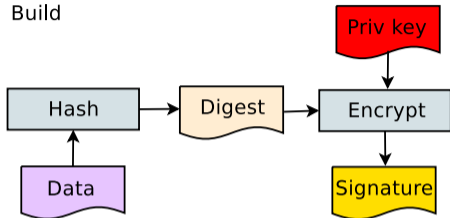


- ▶ At **build** time:
 - ▶ stages are signed
 - ▶ stages embed the public key of next
- ▶ At **boot** time, each stage verify the signature the next one
- ▶ Next stage isn't loaded when the authentication fails

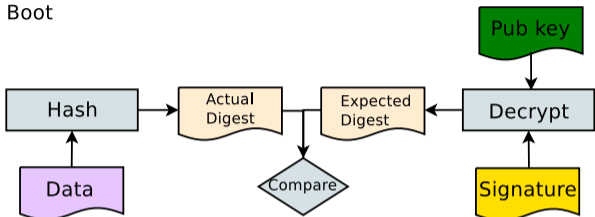


Signature process

Build



Boot



- ▶ Based on digest and asymmetric keys
- ▶ The private key
 - ▶ It is used to sign at build
 - ▶ It **must** not be published
- ▶ The public key
 - ▶ It is used to verify at boot
 - ▶ It is shared



Workflows impacts

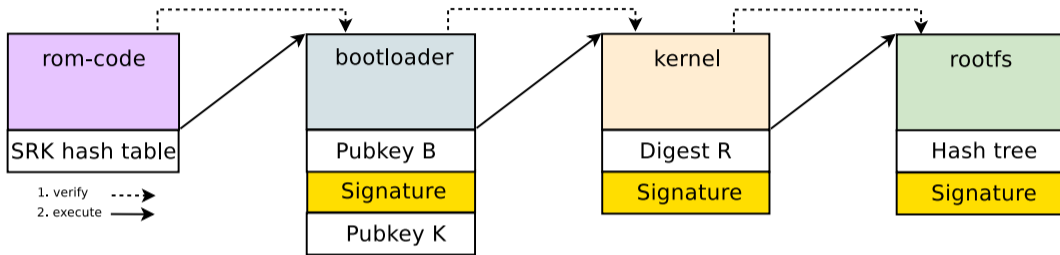
- ▶ Keys management
- ▶ Manufactory
- ▶ Upgrade
- ▶ boot time



A secure boot implementation on i.MX8



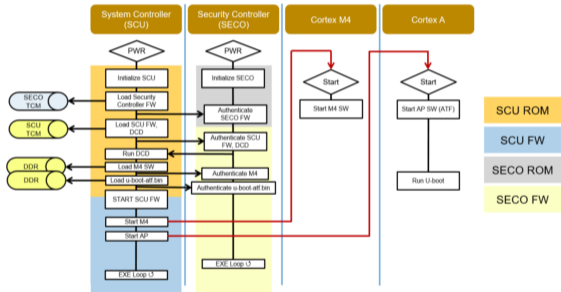
Global view



- ▶ **AHAB** to check the Bootloader integrity, from **ROM code**
- ▶ **U-boot verified boot** to check the kernel integrity, from **U-boot**
- ▶ **dm-verity** to check the rootfs integrity, from the **kernel**
- ▶ **dm-init** and a **boot script** so as not to need initramfs.



ROM code: NXP i.MX8 secure boot

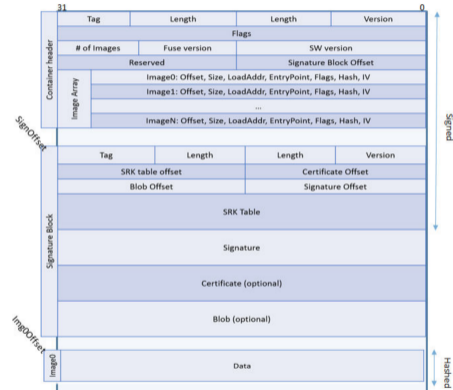
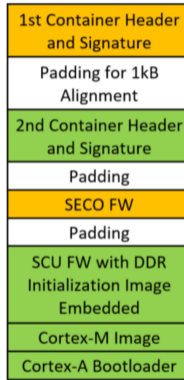


- ▶ Called Advanced High Assurance Boot (AHAB)
- ▶ Different from HAB, the image uses three containers
- ▶ Uses asymmetric keys (PKI tree)
- ▶ Signed by i.MX code signing tool (CST) at build
- ▶ Uses One-Time programmable (OTP) to store SRK
- ▶ Status can be checked from U-boot with `hab_status`
- ▶ Cryptographic Acceleration and Assurance Module (CAAM)



ROM code: AHAB image layout

- ▶ SECO FW using NXP signatures
- ▶ SCFW, SPL and M4 images using OEM signatures
- ▶ U-boot and ATF, loaded by SPL
- ▶ Operations perform by the SECO FW through the SCU ROM





ROM code: Generating PKI tree

- ▶ Set the certificate ID:

```
echo 00000001 > serial
```

- ▶ Set the passphrase to store the private key:

```
echo -e "mypassphrase\nmypassphrase" > key_pass.txt
```

- ▶ Generating a P384 ECC PKI tree:

```
./ahab_pki_tree.sh  
[...]  
Do you want to use an existing CA key (y/n)?: n  
Do you want to use Elliptic Curve Cryptography (y/n)?: y  
Enter length for elliptic curve to be used for PKI tree:  
Possible values p256, p384, p521: p384  
Enter the digest algorithm to use: sha384  
Enter PKI tree duration (years): 10  
Do you want the SRK certificates to have the CA flag set? (y/n)?: n
```



▶ Generating SRK Table and SRK Hash:

```
cd ../crts/  
../linux64/bin/srktool -a -s sha384 -t SRK_1_2_3_4_table.bin \  
-e SRK_1_2_3_4_fuse.bin -f 1 -c \  
SRK1_sha384_secp384r1_v3_usr_cert.pem,\  
SRK2_sha384_secp384r1_v3_usr_cert.pem,\  
SRK3_sha384_secp384r1_v3_usr_cert.pem,\  
SRK4_sha384_secp384r1_v3_usr_cert.pem
```

▶ Checking SRK table matches with the SRK fuse:

```
od -t x4 --endian=big SRK_1_2_3_4_fuse.bin  
sha512sum SRK_1_2_3_4_table.bin
```



ROM code: CST configuration

```
[Header]
Target = AHAB
Version = 1.0
[Install SRK]
# SRK table generated by srktool
File = "crts/SRK_1_2_3_4_table.bin"
# Public key certificate in PEM format
Source = "crts/SRK1_sha384_secp384r1_v3_usr_cert.pem"
# Index of the public key certificate within the SRK table (0 .. 3)
Source index = 0
# Type of SRK set (NXP or OEM)
Source set = OEM
# bitmask of the revoked SRKs
Revocations = 0x0
[Authenticate Data]
# Binary to be signed generated by mkimage
File = "flash.bin.nosigned"
# Offsets = Container header      Signature block (printed out by mkimage)
Offsets   = 0x400                  0x590
```



ROM code: One-Time programmable

► Program fuses:

```
=> fuse prog 0 730 0xbef4d897
=> fuse prog 0 731 0x6abedffa
=> fuse prog 0 732 0xaf28b37c
=> fuse prog 0 733 0xbd3c149a
=> fuse prog 0 734 0xb9bf25cd
=> fuse prog 0 735 0xb23f7389
=> fuse prog 0 736 0x86a0b06f
=> fuse prog 0 737 0xd25485c2
=> fuse prog 0 738 0xcfe655a4
=> fuse prog 0 739 0xe5e7a92e
=> fuse prog 0 740 0xf18dfa06
=> fuse prog 0 741 0x43d7dbc6
=> fuse prog 0 742 0x3a59e53b
=> fuse prog 0 743 0x78c7bf59
=> fuse prog 0 744 0xe7c860bd
=> fuse prog 0 745 0xd8b27ab0
```

► Read fuses:

```
=> fuse read 0 730
=> fuse read 0 731
=> fuse read 0 732
=> fuse read 0 733
=> fuse read 0 734
=> fuse read 0 735
=> fuse read 0 736
=> fuse read 0 737
=> fuse read 0 738
=> fuse read 0 739
=> fuse read 0 740
=> fuse read 0 741
=> fuse read 0 742
=> fuse read 0 743
=> fuse read 0 744
=> fuse read 0 745
```




ROM code: Check status

▶ Check the status of secure:

```
=> ahab_status
Lifecycle: 0x0020, NXP closed
No SECO Events Found!
```

▶ SECO event is raised in case of issue:

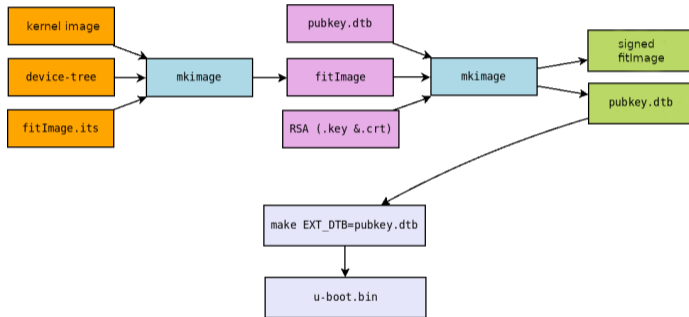
```
=> ahab_status
Lifecycle: 0x0020, NXP closed
SECO Event[0] = 0x0087EE00
    CMD = AHAB_AUTH_CONTAINER_REQ (0x87)
    IND = AHAB_NO_AUTHENTICATION_IND (0xEE)
sc_seco_get_event: idx: 1, res:3
```

▶ Close the device:

```
=> ahab_close
=> reset
=> ahab_status
Lifecycle: 0x0080, OEM closed
No SECO Events Found!
```



bootloader: U-boot verified boot



- ▶ Uses fitimage
- ▶ Uses asymmetric key
- ▶ Signed by `mkimage`



bootloader: fitimage is a container

```
/dts-v1/;

/ {
    description = "U-Boot fitImage for bar";
    #address-cells = <1>;

    images {
        kernel@1 {
            description = "Linux kernel";
            data = /incbin/"fitImage-linux.bin";
            type = "kernel";
            arch = "arm64";
            os = "linux";
            compression = "gzip";
            load = <0x80280000>;
            entry = <0x80280000>;
            hash@1 {
                algo = "sha256";
            };
        };
        fdt@1 {
            description = "Flattened Device Tree blob";
            data = /incbin/"foo.dtb";
            type = "flat_dt";
            arch = "arm64";
            compression = "none";
            load = <0x83000000>;
            hash@1 {
                algo = "sha256";
            };
        };
    };
};
```

```
bootscr@1 {
    description = "U-boot script";
    data = /incbin/"boot.scr";
    type = "script";
    arch = "arm64";
    compression = "none";
    hash@1 {
        algo = "sha256";
    };
};

configurations {
    default = "conf@1";
    conf@1 {
        description = "kernel, dtb, bootscr";
        kernel = "kernel@1";
        fdt = "fdt@1";
        bootscr = "bootscr@1";
        hash@1 {
            algo = "sha256";
        };
    };
};
```

- ▶ To store some `images`:
 - ▶ Some kernel images
 - ▶ Some device tree binaries or overlays
 - ▶ Some boot script
 - ▶ Some FPGA bitstreams...
- ▶ But also some `configurations` that are combinations of images.



bootloader: How the fitimage is signed

- ▶ Isn't globally signed
- ▶ There are two available ways:
 - ▶ Sign images
 - ▶ Sign configurations
- ▶ Sign the configurations allows to prevent mix-and-match attack

```
conf@1 {
    description = "1 Linux kernel, FDT blob, boot script";
    kernel = "kernel@1";
    fdt = "fdt@1";
    bootscr = "bootscr@1";
    hash@1 {
        algo = "sha256";
    };
    signature@1 {
        algo = "sha256,rsa4096";
        key-name-hint = "kernel-dev";
        sign-images = "kernel", "fdt", "bootscr";
    };
};
```



bootloader: Generating keys and the certificate

- ▶ Generate a private key

```
openssl genpkey -algorithm RSA -out kernel-dev.key -pkeyopt rsa_keygen_bits:4096
```

- ▶ Generate a certificat

```
openssl req -new -x509 -key kernel-dev.key -out kernel-dev.crt
```

- ▶ Generate a public key

```
openssl rsa -pubout -in kernel-dev.key -out kernel-dev.pem
```

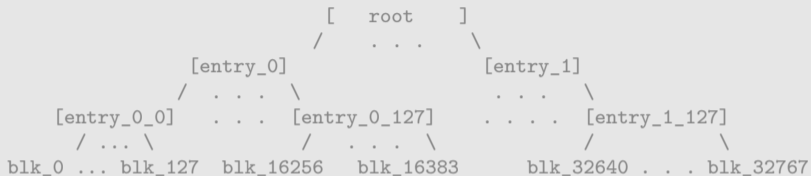


bootloader: Build the signed fitimage

```
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
```



rootfs: dm-verity



- ▶ Virtual layer provides integrity checking
- ▶ Using cryptographic hash tree (Merkle tree)
- ▶ Blocks are hashed and the value is checked **only on access**
- ▶ Only for read-only block devices
- ▶ Data and hash device can be the same
- ▶ Since 5.4, the root hash can be signed



▶ Create hash on the image:

```
veritysetup format verify --hash-offset=${OFFSET} image.squashfs image.squashfs
VERITY header information for image.squashfs
UUID:                5f1872a8-6bd0-4824-82fc-886b944b60c2
Hash type:           1
Data blocks:         12800
Data block size:     4096
Hash block size:     4096
Hash algorithm:      sha256
Salt:
73be30a3f4338cd9046492b9abcb172bb6fe4b741e9104cc7cf768dbd0901547
Root hash:
408323fad51d3a85c26384270da3980a63874b67d1e30a47330bd163bba98a41
```

▶ Verify the image:

```
veritysetup verify --hash-offset=${OFFSET} image.squashfs image.squashfs ${HASH_ALG}
```

▶ Open the image:

```
veritysetup open --hash-offset=${OFFSET} image.squashfs foo image.squashfs ${KEY} ${SALT}
dmsetup table --concise
foo,5f1872a8-6bd0-4824-82fc-886b944b60c2,1,ro,0 905896
verity 1 7:0 7:0 4096 4096 113237 113238 sha256
```




rootfs: dm-init

- ▶ Early create device mapper from kernel cmdline

```
dm-mod.create="rootfs,,0,ro,0 905880 verity 1 /dev/mmcblk0p2 /dev/mmcblk0p2 4096 4096 113235 113236 sha256 76defbdb8fd7842ab708b2b23ee718ec46dda3e41367462d12ad8c793cedfc763a7ea567e63eabf5c18fa938573e5e16e2fe81b440267751bd8a8fd70d22f8db"
```

- ▶ Allows to mount dm-verity device
 - ▶ **Without** `initramfs` and `veritysetup`
 - ▶ **Only with** a boot script that extend the kernel cmdline:

```
source ${fitimage_loadaddr}:bootscr@1  
sha256+
```

- ▶ Boot script example:

```
setenv sectors 244184  
setenv data_blocks 30523  
setenv hash_start 30524  
setenv data_block_sz 4096  
setenv hash_block_sz 4096  
setenv hash_alg sha256  
setenv salt e2f254232415ea2c694c8064bc62169e895ab56f0d6f6b0db9a8734f5a4759d4  
setenv root_hash bf67ab59b4b09263da1306e996f35f515c54c9c4078cbf6ecb629fcea3afee99  
setenv bootargs ${bootargs} rootfstype=squashfs root=/dev/dm-0 dm-mod.create="rootfs,,0,ro,0 ${sectors} verity 1 /dev/mmcblk0p2 /dev/mmcblk0p2 ${data_block_sz} ${hash_block_sz} \  
${data_blocks} ${hash_start} ${hash_alg} ${root_hash} ${salt}"
```

Questions? Suggestions? Comments?

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<https://bootlin.com/pub/conferences/2021/lee/perrot-secure-boot/>