Embedded Linux size reduction techniques

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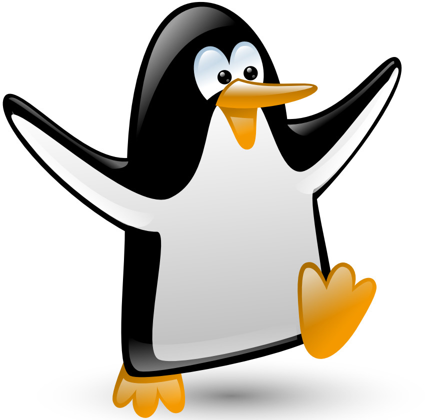
Michael Opdenacker

- Michael Opdenacker
- Founder and Embedded Linux engineer at Bootlin
  - Embedded Linux **expertise**
  - **Development**, consulting and training
  - Strong open-source focus
- Long time interest in embedded Linux boot time, and one of its prerequisites: small system size.
- From **Orange**, France



Penguin from Justin Ternet

(https://openclipart.org/detail/182875/pinguin)

Why reduce size?

There are multiple reasons for having a small kernel and system

- Run on very small systems (IoT)
- Run Linux as a bootloader
- Boot faster (for example on FPGAs)
- Reduce power consumption
  Even conceivable to run the whole system in CPU internal RAM or cache (DRAM is power hungry and needs refreshing)
- Security: reduce the attack surface
- Cloud workloads: optimize instances for size and boot time.
- Spare as much RAM as possible for applications and maximizing performance.

See `https://tiny.wiki.kernel.org/use_cases`

Reasons for this talk

- No talk about size since ELCE 2015
- Some projects stalled (Linux tinification, LLVM Linux...)
- Opportunity to have a look at solutions I didn't try: musl library, Toybox, gcc LTO, new gcc versions, compiling with Clang...
- Good to have a look again at that topic, and gather people who are still interested in size, to help them and to collect good ideas.
- Good to collect and share updated figures too.

How small can a normal Linux system be?

- RAM
  - You need 2-6 MB of RAM for an embedded kernel
  - Need at least 8-16 MB to leave enough space for user-space (if user-space is not too complex)
  - More RAM helps with performance!
- Storage
  - You need 2-4 MB of space for an embedded kernel
  - User space can fit in a few hundreds of KB.
  - With a not-too-complex user-space, 8-16 MB of storage can be sufficient.

Compiler optimizations

- *gcc* offers an easy-to-use `-Os` option for minimizing binary size.
- It is essentially the optimizations found in `-O2` without the ones that increase size

See `https://gcc.gnu.org/onlinedocs/gcc/Optimize-Options.html` for all available optimizations

Using a recent compiler

Compiling for ARM versatile, Linux 4.10

- With gcc 4.7: 407512 bytes (zImage)
- With gcc 6.2: 405968 bytes (zImage, -0.4%)

A minor gain!

Using gcc LTO optimizations

LTO: Link Time Optimizations

- Allows gcc to keep extra source information to make further optimizations at link time, linking multiple object files together. In particular, this allows to remove unused code.
- Even works with programs built from a single source file! Example: `oggenc` from `http://people.csail.mit.edu/smcc/projects/single-file-programs/oggenc.c` (1.7 MB!)
- How to compile with LTO:
  `gcc -Os -flto oggenc.c -lm`

See again `https://gcc.gnu.org/onlinedocs/gcc/Optimize-Options.html` for details.

gcc LTO optimizations results

Compiling `oggenc.c`

- With gcc 6.2 for x86_64:
  - **Without LTO**: 2122624 bytes (unstripped), 1964432 bytes (stripped)
  - **With LTO**: 2064480 bytes (unstripped, -2.7%), 1915016 bytes (stripped, -**2.6%**)
- With gcc 6.2 for armelhf:
  - **Without LTO**: 1157588 bytes (unstripped), 1018972 bytes (stripped)
  - **With LTO**: 1118480 bytes (unstripped, -3.4%), 990248 bytes (stripped, -**2.8%**)

Note: the x86_64 size is not meant to be compared with arm code. 64 bit code is bigger than 32 bit code, that's expected.

gcc vs clang

Let's try to compile `oggenc.c` again:

- Compiled with **gcc** 6.2.0 on x86_64:
  `gcc oggenc.c -lm -Os; strip a.out`
  Size: 1964432 bytes
- Compiled with **clang** 3.8.1 on x86_64:
  `clang oggenc.c -lm -Os; strip a.out`
  Size: 1865592 bytes **(-5%)**
- gcc can catch up a little with the LTO option:
  `gcc oggenc.c -lm -flto -Os; strip a.out`
  Size: 1915016 bytes (-2.7%)

Note that gcc can win for very small programs (-1.2 % vs clang on `hello.c`).

ARM: arm vs thumb instruction sets

- In addition to the *arm 32 bit instruction set*, the ARM 32 bit architecture also offers the *Thumb instruction set*, which is supposed to be more compact.
- You can use `arm-linux-objdump -S` to distinguish between arm and thumb code.

Arm code

32 bit instructions

```
00011288 <main>:
   11288:       e92d4870        push    {r4, r5, r6, fp, lr}
   1128c:       e28db010        add     fp, sp, #16
   11290:       e24ddf61        sub     sp, sp, #388     ; 0x184
```

Addresses multiples of 4

Thumb code

16 bit instructions

```
00011288 <main>:
   11288:       b5f0            push    {r4, r5, r6, r7, lr}
   1128a:       b0e5            sub     sp, #404        ; 0x194
   1128c:       af06            add     r7, sp, #24
```

Addresses multiples of 2

ARM: arm vs thumb instruction sets (2)

- To compile in arm mode:
  `arm-linux-gnueabihf-gcc -marm oggenc.c -lm`
  Result: 1323860 bytes
- To compile in thumb mode (default mode for my compiler!):
  `arm-linux-gnueabihf-gcc -mthumb oggenc.c -lm`
  Result: 1233716 bytes (**-6.8%**)
- Notes:
  - Thumb instructions are more compact but more are needed, which explains the limited size reduction.
  - Thumb mode can be the default for your compiler!
  - In my tests with `-marm`, the binary was a mix of Arm and Thumb code.

How to get a small kernel?

- Run `make tinyconfig` (since version 3.18)
- `make tinyconfig` is `make allnoconfig` plus configuration settings to reduce kernel size
- You will also need to add configuration settings to support your hardware and the system features you need.

```
tinyconfig:
	$(Q)$(MAKE) -f $(srctree)/Makefile allnoconfig tiny.config
```

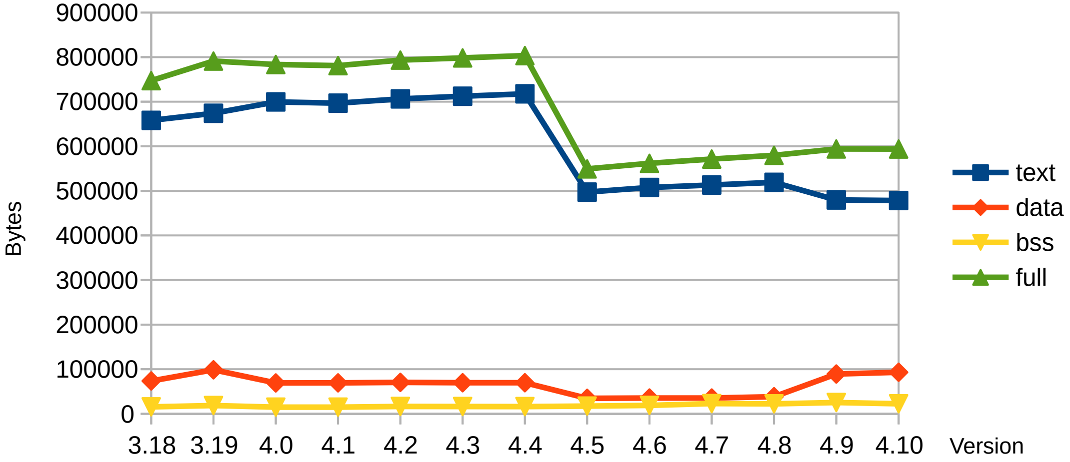
kernel/configs/tiny.config

```
# CONFIG_CC_OPTIMIZE_FOR_PERFORMANCE is not set
CONFIG_CC_OPTIMIZE_FOR_SIZE=y
# CONFIG_KERNEL_GZIP is not set
# CONFIG_KERNEL_BZIP2 is not set
# CONFIG_KERNEL_LZMA is not set
CONFIG_KERNEL_XZ=y
# CONFIG_KERNEL_LZO is not set
# CONFIG_KERNEL_LZ4 is not set
CONFIG_OPTIMIZE_INLINING=y
# CONFIG_SLAB is not set
# CONFIG_SLUB is not set
CONFIG_SLOB=y
```

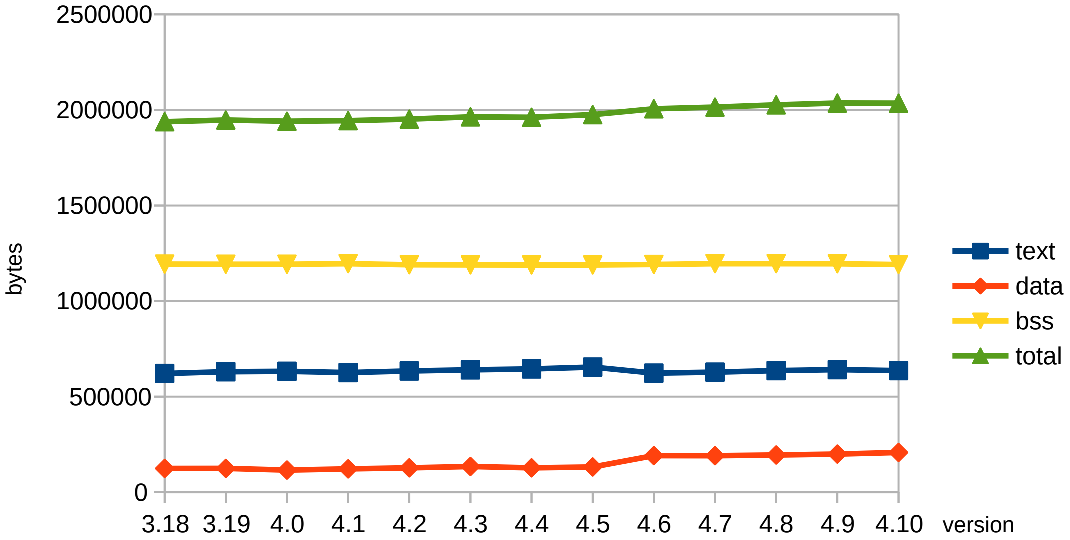
arch/x86/configs/tiny.config

```
CONFIG_NOHIGHMEM=y
# CONFIG_HIGHMEM4G is not set
# CONFIG_HIGHMEM64G is not set
```

tinyconfig Linux kernel size (arm)



tinyconfig Linux kernel size (x86)



Linux kernel size notes

- We reported the `vmlinux` file size, to reflect the size that the kernel would use in RAM.
- However, the `vmlinux` file was not stripped in our experiments. You could get smaller results.
- On the other hand, the kernel will make allocations at runtime too. Counting on the stripped kernel size would be too optimistic.

Kernel size on a system that boots

Linux 4.10 booting on QEMU ARM VersatilePB

- `zImage`: 405472 bytes
- text: 972660
- data: 117292
- bss: 22312
- total: 1112264

Minimum RAM I could boot this kernel with: 4M (3M was too low). Not worse than 10 years back!

State of the kernel tinification project

- Stalled since Josh Triplett's patches were removed from the *linux-next* tree
- See `https://lwn.net/Articles/679455`
- Patches still available on `https://git.kernel.org/cgit/linux/kernel/git/josh/linux.git/`
- Removing functionality through configuration settings may no longer be the way to go, as the complexity of kernel configuration parameter is already difficult to manage.
- The future may be in automatic removal of unused features (system calls, command line options, `/proc` contents, kernel command line parameters...)
- Lack of volunteers with time to drive the mainlining effort anyway.

Follow the kernel developers discussion about this topic: `https://lwn.net/Articles/608945/`. That was in 2014!

gcc LTO and the Linux kernel

Patches proposed by Andi Kleen in 2012

- Such optimizations would allow performance improvements as well as some size reduction by eliminating unused code (-6% on ARM, reported by Tim Bird).
- The last time the LTO patches were proposed, using LTO could create new issues or make problems harder to investigate. Linus didn't trust the toolchains at that time.
- See `https://lwn.net/Articles/512548/`

Kernel XIP

XIP: eXecution In Place

- Allows to keep the kernel text in flash (NOR flash required).
- Only workable solution for systems with very little RAM
- ARM is apparently the only platform supporting it

How to help with kernel tinification (1)

- Look for obj-y in kernel Makefiles:

```
obj-y     = fork.o exec_domain.o panic.o \
            cpu.o exit.o softirq.o resource.o \
            sysctl.o sysctl_binary.o capability.o ptrace.o user.o \
            signal.o sys.o kmod.o workqueue.o pid.o task_work.o \
            extable.o params.o \
            kthread.o sys_ni.o nsproxy.o \
            notifier.o ksysfs.o cred.o reboot.o \
            async.o range.o smpboot.o ucount.o
```

- What about allowing to compile Linux without ptrace support (14K on arm) or without reboot (9K)?
- Another way is to look at the compile logs and check whether/why everything is needed.

How to help with kernel tinification (2)

- Look for tinification opportunities, looking for the biggest symbols:
  `nm --size-sort vmlinux`
- Look for size regressions with the *Bloat-O-Meter*:

```
> ./scripts/bloat-o-meter vmlinux-4.9 vmlinux-4.10
add/remove: 101/135 grow/shrink: 155/109 up/down: 19517/-19324 (193)
function                                     old     new   delta
page_wait_table                                -    2048   +2048
sys_call_table                                 -    1600   +1600
cpuhp_bp_states                              980    1800    +820
...
```

LLVM Linux project

http://llvm.linuxfoundation.org/

- Using Clang to compile the Linux kernel also opens the door to performance and size optimizations, possibibly even better than what you can get with gcc LTO.
- Unfortunately, the project looks stalled since 2015.
- News: Bernhard Rosenkränzer from Linaro has updated the patchset and should start pushing upstream soon. Reference: https://android-git.linaro.org/kernel/hikey-clang.git, branch android-hikey-linaro-4.9-clang

Userspace - BusyBox vs Toybox

```
___ [        4096]  bin
___ ___ [      100324]  busybox
___ ___ [           7]  cat -> busybox
___ ___ [           7]  dmesg -> busybox
___ ___ [           7]  hush -> busybox
___ ___ [           7]  ls -> busybox
___ ___ [           7]  mkdir -> busybox
___ ___ [           7]  mount -> busybox
___ ___ [           7]  mv -> busybox
___ ___ [           7]  ps -> busybox
___ ___ [           7]  rm -> busybox
___ ___ [           7]  sh -> busybox
___ ___ [           7]  umount -> busybox
___ [        4096]  sbin
    ___ [          14]  ifconfig -> ../bin/busybox
    ___ [          14]  init -> ../bin/busybox
    ___ [          14]  modprobe -> ../bin/busybox
    ___ [          14]  rmmod -> ../bin/busybox

2 directories, 16 files
```

```
___ [        4096]  bin
___ ___ [           6]  cat -> toybox
___ ___ [           6]  dmesg -> toybox
___ ___ [           6]  ls -> toybox
___ ___ [           6]  mkdir -> toybox
___ ___ [           6]  mount -> toybox
___ ___ [           6]  mv -> toybox
___ ___ [           6]  rm -> toybox
___ ___ [           6]  sh -> toybox
___ ___ [       84396]  toybox
___ ___ [           6]  toysh -> toybox
___ ___ [           6]  umount -> toybox
___ [        4096]  sbin
___ ___ [          13]  ifconfig -> ../bin/toybox
___ ___ [          13]  init -> ../bin/toybox
___ ___ [          13]  modprobe -> ../bin/toybox
___ ___ [          13]  rmmod -> ../bin/toybox
___ [        4096]  usr
    ___ [        4096]  bin
        ___ [          16]  ps -> ../../bin/toybox

4 directories, 16 files
```

Compiled on ARM with gcc 5.4 (dynamically linked with glibc)

BusyBox vs Toybox - shell only

```
.
└── [       4096]  bin
    ├── [      59152]  busybox
    ├── [          7]  hush -> busybox
    └── [          7]  sh -> busybox

1 directory, 3 files
```

```
.
└── [       4096]  bin
    ├── [          6]  dmesg -> toybox
    ├── [          6]  sh -> toybox
    ├── [      18224]  toybox
    └── [          6]  toysh -> toybox

1 directory, 4 files
```

Compiled on ARM with gcc 5.4 (dynamically linked with glibc)

BusyBox vs Toybox - Conclusions

- Toybox wins if your goal is to reduce size and have a tiny rootfs
- BusyBox wins in terms of configurability, and in terms of functionality for more elaborate needs.
- Comments from Rob Landley: the Toybox shell is too experimental to be used at the moment, and is meant to become a bash replacement. If you're looking for a small shell, you may look at *mksh* (`https://www.mirbsd.org/mksh.htm`)

glibc vs uclibc vs musl (static)

Let's compile and strip BusyBox 1.26.2 **statically** and compare the size

- With gcc 6.3, armel, musl 1.1.16:
  183348 bytes
- With gcc 6.3, armel, uclibc-ng 1.0.22 :
  210620 bytes.
- With gcc 6.2, armel, glibc:
  755088 bytes

Note: BusyBox is automatically compiled with `-Os` and stripped.

glibc vs uclibc vs musl (dynamic)

Let's compile and strip BusyBox 1.26.2 **dynamically** and compare the size

- With gcc 6.3, armel, musl 1.1.16:
  92948 bytes
- With gcc 6.3, armel, uclibc-ng 1.0.22 :
  92116 bytes.
- With gcc 6.2, armel, glibc:
  100336 bytes

glibc vs uclibc vs musl - small static executables

Let's compile and strip a `hello.c` program **statically** and compare the size

- With gcc 6.3, armel, musl 1.1.16:
  7300 bytes
- With gcc 6.3, armel, uclibc-ng 1.0.22 :
  67204 bytes.
- With gcc 6.2, armel, glibc:
  492792 bytes

Using super strip

`sstrip` (`http://www.muppetlabs.com/~breadbox/software/elfkickers.html`) removes ELF contents that are not needed for program execution.

- Expect to save only a few hundreds or thousands of bytes
- `sstrip` is architecture independent (unlike `strip`) and is trivial to compile

Example with the small static program we've just compiled:

- With gcc 6.3, armel, musl 1.1.16: 7300 to 6520 bytes (-780)
- With gcc 6.3, armel, uclibc-ng 1.0.22: 67204 bytes to 66144 bytes (-1060)
- With gcc 6.2, armel, glibc: 492792 to 491208 bytes (-1584)

With BusyBox statically compiled with the musl library:

- From 183012 to 182289 (-723)

Other lightweight libraries

- **diet libc** (`http://www.fefe.de/dietlibc/`
  - Latest release in 2013! Not supported by toolchain generators.
  - Was meant to generate small static executables
- **klibc** (`https://www.kernel.org/pub/linux/libs/klibc/`)
  - Latest release in 2014! Not supported by toolchain generators.
  - Was meant to generate small static executables for use in initramfs filesystems.
  - Need reviving?

Optimizing libraries

- You can use *mklibs* (`git://anonscm.debian.org/d-i/mklibs`, but that just copies the libraries which are used for a given set of executables. Build systems can already do that.
- Would need something that removes unused symbols from libraries. Is the Library Optimizer from MontaVista (`https://sourceforge.net/projects/libraryopt/`) still usable?

Achieving small filesystem size

- For very small systems, booting on an initramfs is the best solution. It allows to boot earlier and faster too (no need for filesystem and storage drivers).
- A single static executable helps too (no libraries)
- For bigger sizes, compressing filesystems are useful:
  - SquashFS for block storage
  - JFFS2 for flash (UBI has too much overhead for small partitions)
  - ZRAM (compressed block device in RAM)

Conclusions

- Though there apparently hasn't been recent mainlining efforts, the kernel size can remain very small (405K compressed on ARM, running on a system with 4M of RAM).
- Compilers: use *clang* or *gcc LTO* (not for the kernel yet)
- New C library worth using: *musl*
- Worth giving Toybox a try too, when simple command line utilities are sufficient.
- Still significant room for improvement. Difficult to make things removable without increasing the kernel parameter and testing complexity, though.

BoF part

- Any recent achievements to report?
- Any other resources you are using?
- Volunteers to join the size effort?
- News from the LLVM Linux project?
- Community friendly hardware we could use for development efforts? Supporting special hardware with tight requirements is a good reason for getting code accepted.

Useful resources

- Home of the Linux tinification project https://tiny.wiki.kernel.org/
- Ideas ideas and projects which would be worth reviving http://elinux.org/Kernel_Size_Reduction_Work
- Tim Bird - Advanced size optimization of the Linux kernel (2013) http://events.linuxfoundation.org/sites/events/files/lcjp13_bird.pdf
- Pieter Smith - Linux in a Lightbulb: How Far Are We on Tinification (2015) http://www.elinux.org/images/6/67/Linux_In_a_Lightbulb-Where_are_we_on_tinification-ELCE2015.pdf
- Vitaly Wool - Linux for Microcontrollers: From Marginal to Mainstream (2015) http://www.elinux.org/images/9/90/Linux_for_Microcontrollers-_From_Marginal_to_Mainstream.pdf

Interesting talks at ELC

- Tuesday - 4:20pm
  Tutorial: building the Simplest Possible Linux System - Rob Landley
- Tuesday - 5:20pm
  Optimizing C for Microcontrollers - Best Practices - Khem Raj
- Thursday - 3:30pm
  GCC/Clang Optimizations for Embedded Linux - Khem Raj

Questions? Suggestions? Comments?

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http://bootlin.com/pub/conferences/2017/elc/opdenacker-embedded-linux-size-reduction/

Notes from discussions with the audience (1)

- Bernhard Rosenkränzer suggested to try the Bionic C library from Android in standard Linux. It's not perfect but could be useful in some cases.
- Clang has a new `-Oz` optimization option that goes further than `-Os`
- Rob Landley mentioned his 2013 patchset to address limitations in the initramfs booting approach. See https://lkml.org/lkml/2013/7/9/501

Notes from discussions with the audience (2)

- In the search for a small community friendly board with very little RAM (no more than 2-4 MB of RAM), it seems that the most popular architecture is STM32.
- *Musl* library:
  - To build a *Musl* toolchain, in addition to *Crosstool-ng*, it is also possible to use the *musl-cross-make* project (`https://github.com/richfelker/musl-cross-make`)
  - *Musl* is used in the *Alpine Linux* distribution (`https://www.alpinelinux.org/`, focusing on small size and security. You could use it if your system needs a distribution.