Code size Improvement work in TCWG

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Topics covered

- Investigation in embedded code size GCC vs Clang
- Virtual Function Elimination
- Function Outlining support in Arm

TCWG Code Size Investigation

- Compare Clang and GCC for code-size on embedded systems
- Traditional territory of GNU ARM Embedded Toolchain for Cortex-M and Cortex-R processors
- Compare Clang master (10.0.0) and GCC Trunk (10.0.0)
- Focus on Clang -Oz and GCC -Os for minimum code-size using comparable options
- Primary goal to find out how close Clang is to GCC on code-size
- Secondary goal to record opportunities for improvements
- Choose representative real-world code-bases rather than benchmarks
  - Zephyr (RTOS) for cortex-m4 soft-float and cortex-m0
  - CMSIS-DSP for cortex-m4f

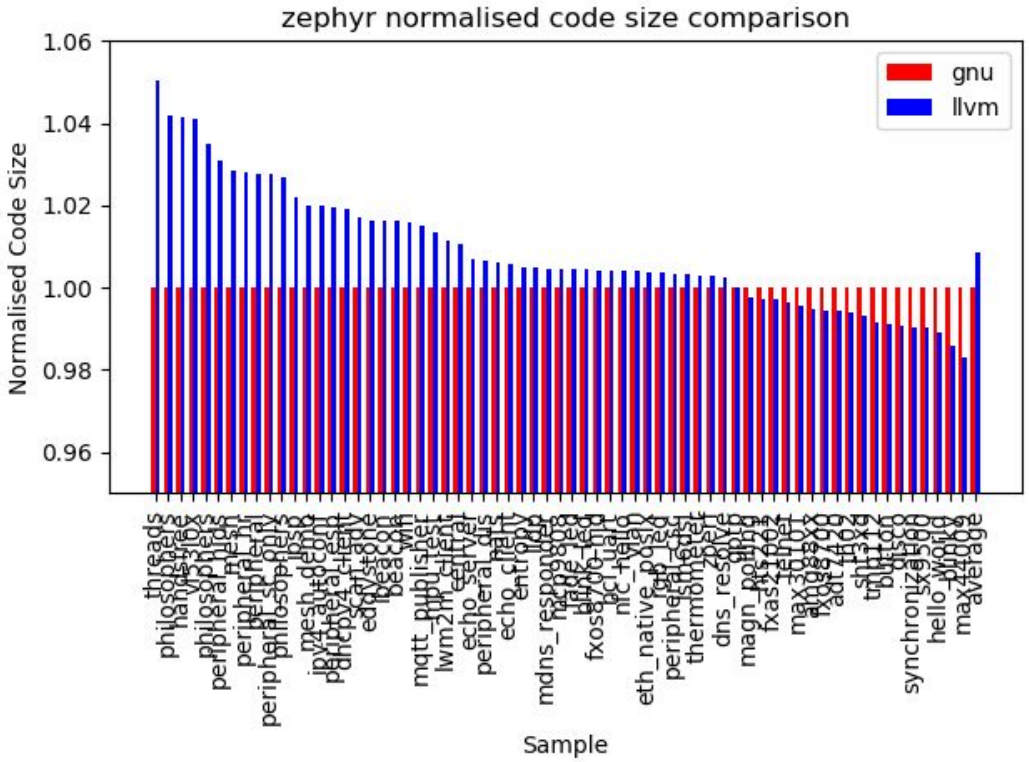
Code size comparison with Zephyr

- Measure code size for a subset of the Zephyr sample applications
- For GCC, use a TCWG built arm-none-eabi-gcc with GNU-RM multilibs
- For Clang, use a TCWG build clang installation using arm-none-eabi-gcc as the linker driver
  - Same libraries and linker, Clang used as assembler and compiler
  - Command line options chosen to match arm-none-eabi-gcc defaults

GCC and Clang code size comparison

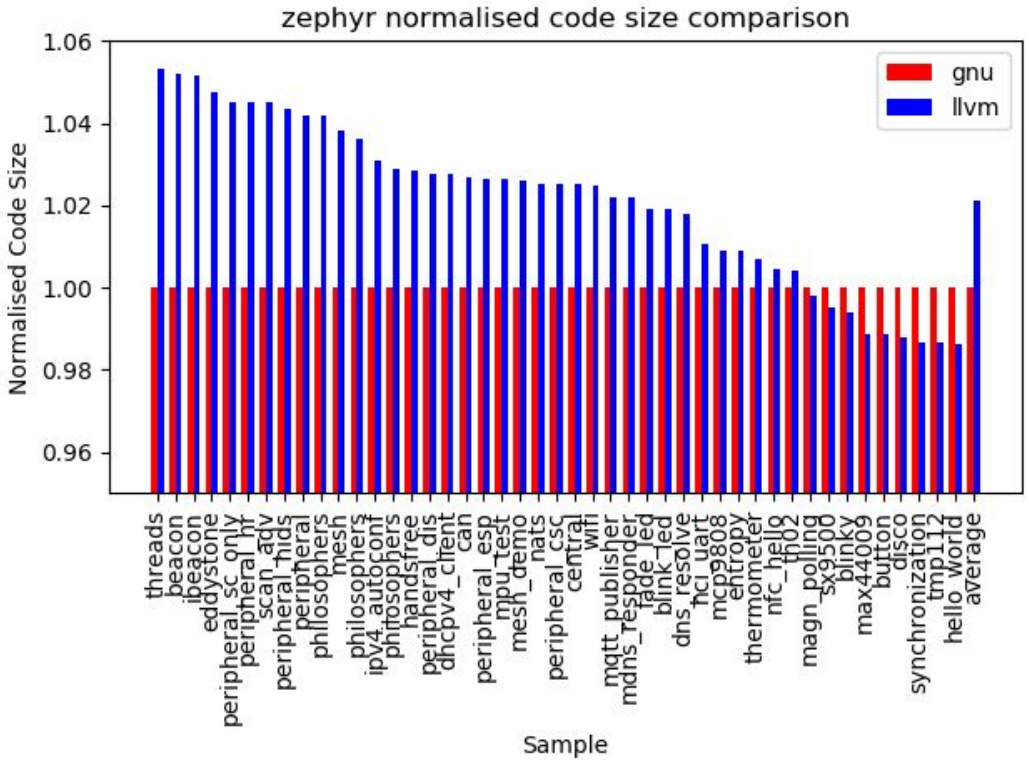
- Measure the size of the executable where possible
  - Comdat groups will be merged by the linker
  - Executable will include helper library code
  - Effect of linker garbage collection on dead code
- Make sure the same binary libraries are used in any comparison
- The size of the .text section is a good proxy for overall code size
- The ELF symbol is a good measurement for a functions code size

Cortex-M4 results normalized to GCC



- Normalizing GCC at 1.0 shows the relative differences more clearly
- Graph y-range is compressed to emphasise differences
- Total LLVM Size 3462456
- Total GCC Size 3424092
- LLVM is 1.1% larger

Cortex-M0 results normalized to GCC



- More samples show larger increases
- Graph y-range is compressed to emphasise differences.
- Cortex-M0 has fewer supported samples.
- Total LLVM Size 2474544
- Total GCC Size 2404132
- LLVM is 2.8% larger

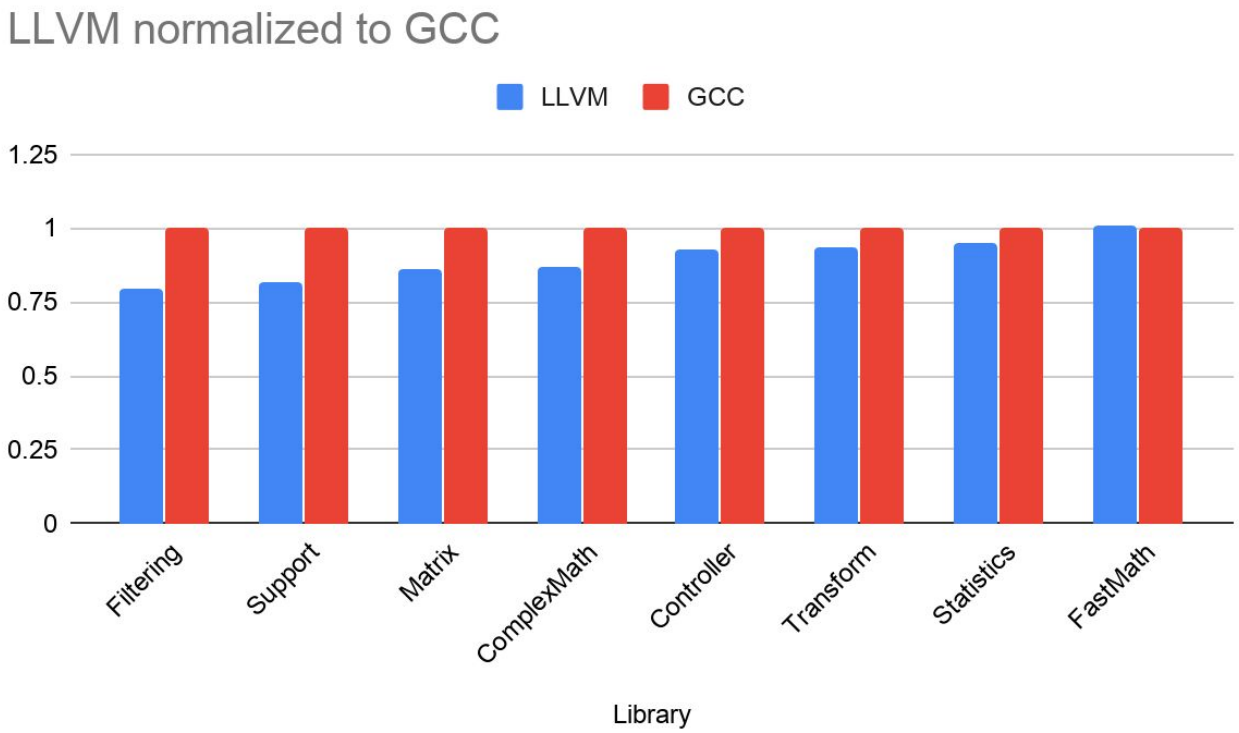
Analysis of results

- On Cortex M4 LLVM is about 1% larger
- On Cortex M0 LLVM is about 2.8% larger
- Amount of C-library and helper library code < 1%
- Common code to all examples about 6000 bytes on M4; 5% of largest example, 60% of hello_world
- Turning off inlining halves the difference
- Fewer spills due to register allocation in GCC
- Many smaller optimizations in aggregate

CMSIS DSP

- Part of the CMSIS library
- Implementations of DSP functions
- Structure of library amenable to examining object files

CMSIS DSP Cortex-M4f normalized to GCC



- Clang is 90% the size of GCC for CMSIS DSP on M4

Analysis of results

- Clang can be substantially smaller than GCC
- Very hard for a non-expert to compare the generated code
- Many smaller things, but can be repeated due to nature of the code
  - GCC inlines `aeabi_llsl` in several places.
  - Clang makes use of rounding instructions such as SMMULR for source that manually rounds.
    - `(q31_t) (((((q63_t) a) << 32) + ((q63_t) x * y) + 0x80000000LL ) >> 32)`

Summary of Code Size investigation

- GCC is on average smaller than Clang for Zephyr for both Cortex-M0 and Cortex-M4
  - Inlining strategy the largest single difference
  - Many small improvements needed
- Cortex-M4 closer (1%) than Cortex-M0 (2.9%)
- Clang generates smaller DSP code for Cortex-M4 in almost all cases
- Specific issues recorded in LLVM-583

Dead Virtual Function Elimination (VFE) in LLVM

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An example we'd like to optimise

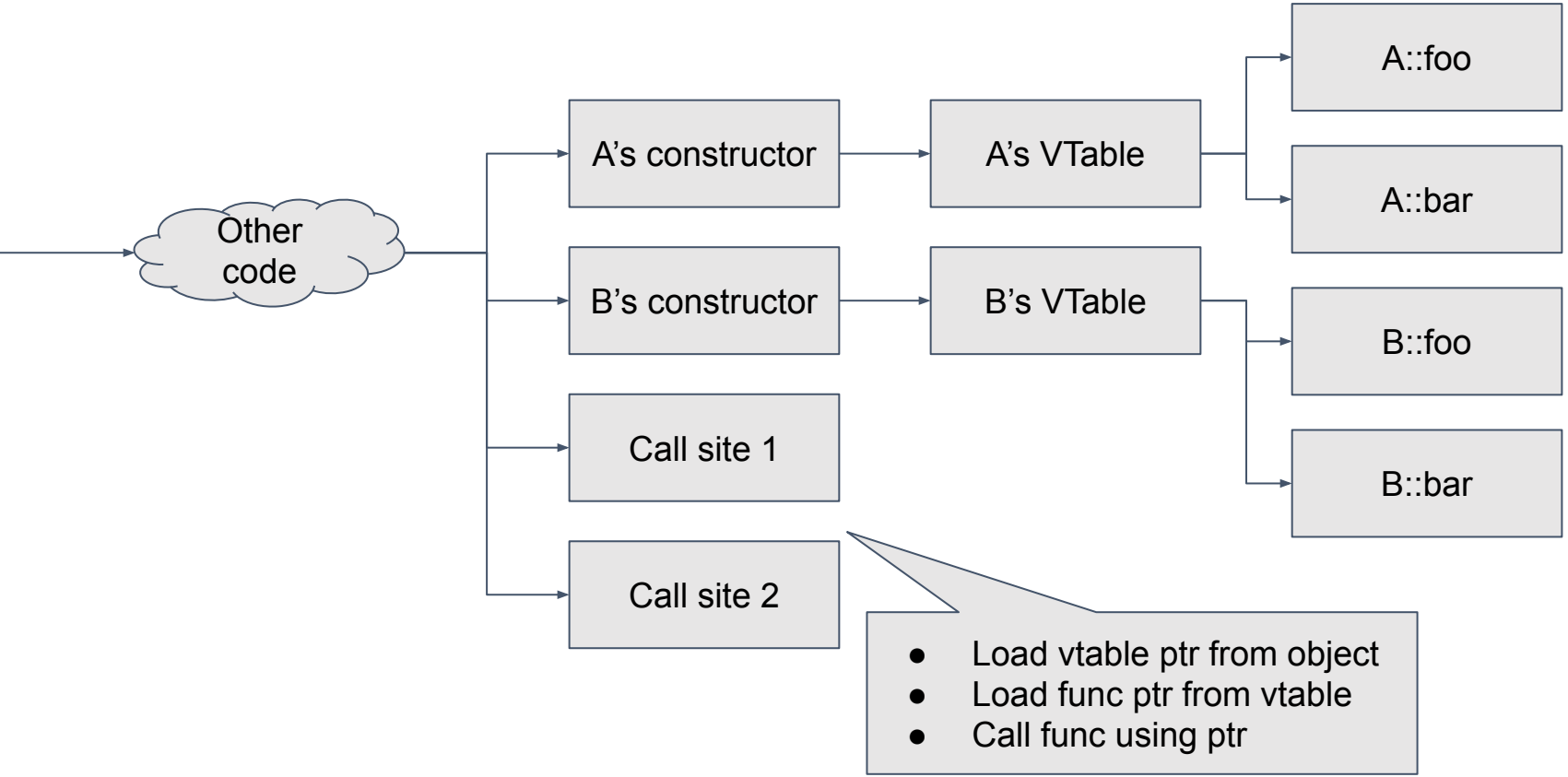
```
struct A {
  virtual int foo() { return 1; }
  virtual int bar() { return 2; }
};

struct B : A {
  virtual int foo() { return 3; }
  virtual int bar() { return 4; }
};

A* make_A() { return new A(); }
B* make_B() { return new B(); }

int call_1(A* p) { return p->foo(); }
int call_2(B* p) { return p->bar(); }
```

No calls to this function

Could call A::foo or B::foo

Can only call B::bar

What does this looks like to GlobalDCE?

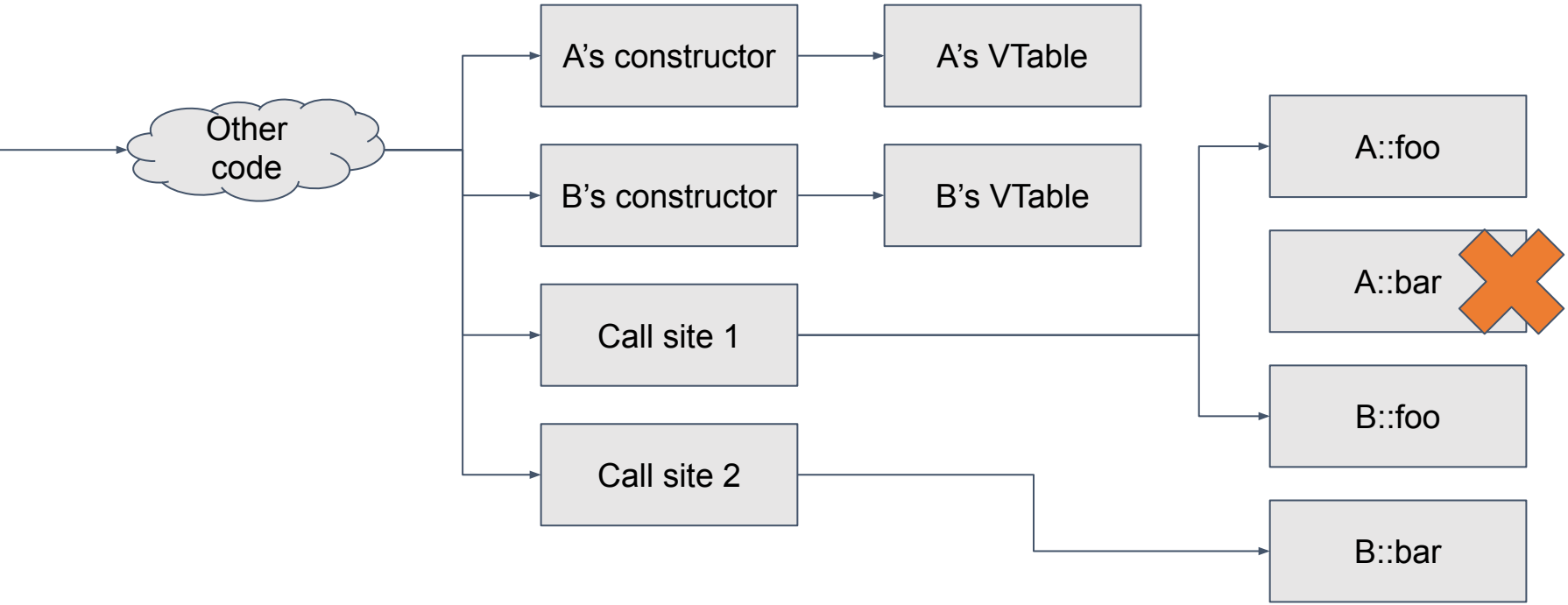


Type metadata

- Optionally added to vtables, virtual call sites
- Provides link between call sites and vtable slots
- Currently used for devirtualisation, control flow integrity
- Needs some changes to call sites to allow VFE

```
@_ZTV1A = constant { [4 x i8*] } ...,  !type !0
@_ZTV1B = constant { [4 x i8*] } ...,  !type !0, !type !4

!0 = !{i64 16, !"_ZTS1A"}
!4 = !{i64 16, !"_ZTS1B"}

%vtable1 = load i8*, i8** %0, align 8, !tbaa !9
%1 = tail call { i8*, i1 } @llvm.type.checked.load(
                                i8* %vtable1, i32  8, metadata !"_ZTS1B")
```

How does this change GlobalDCE's view?

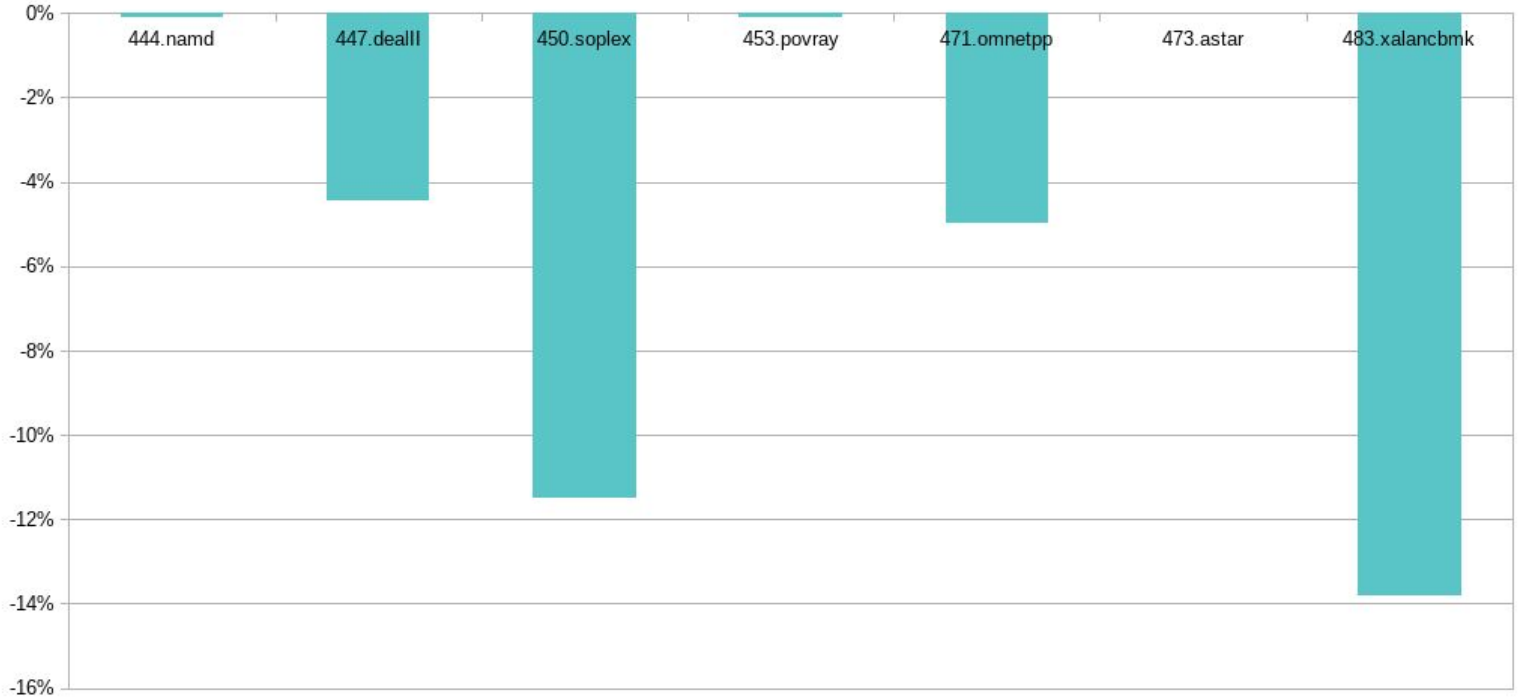


When is this optimisation valid?

- Need to see every possible call site involving a class
- Generally requires `-fvisibility=hidden`, and LTO
- More complicated if related classes have different visibility
  - Most visible base class with a vtable
- Added new `!vcall_visibility` metadata to represent this

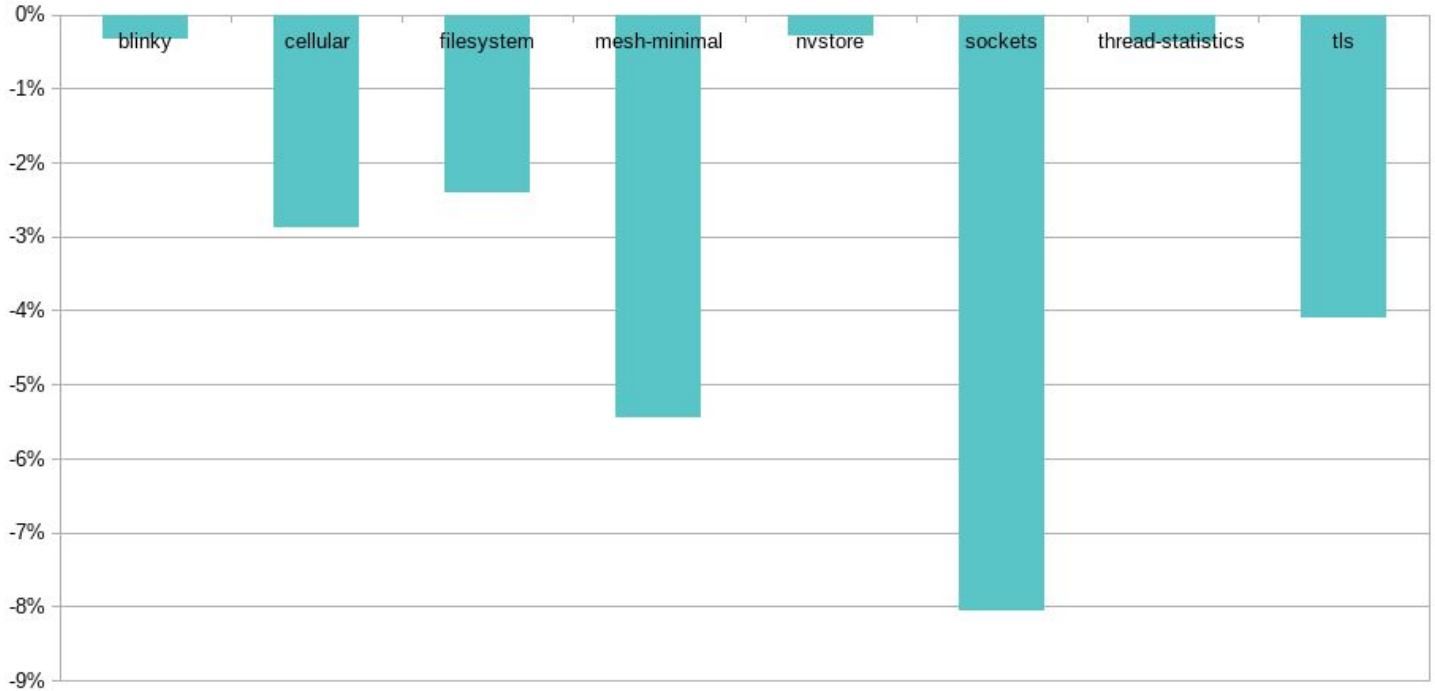
Benchmark - SPEC2006 (C++ subset)

Code size change, compared to -Oz -flto -fvisibility=hidden



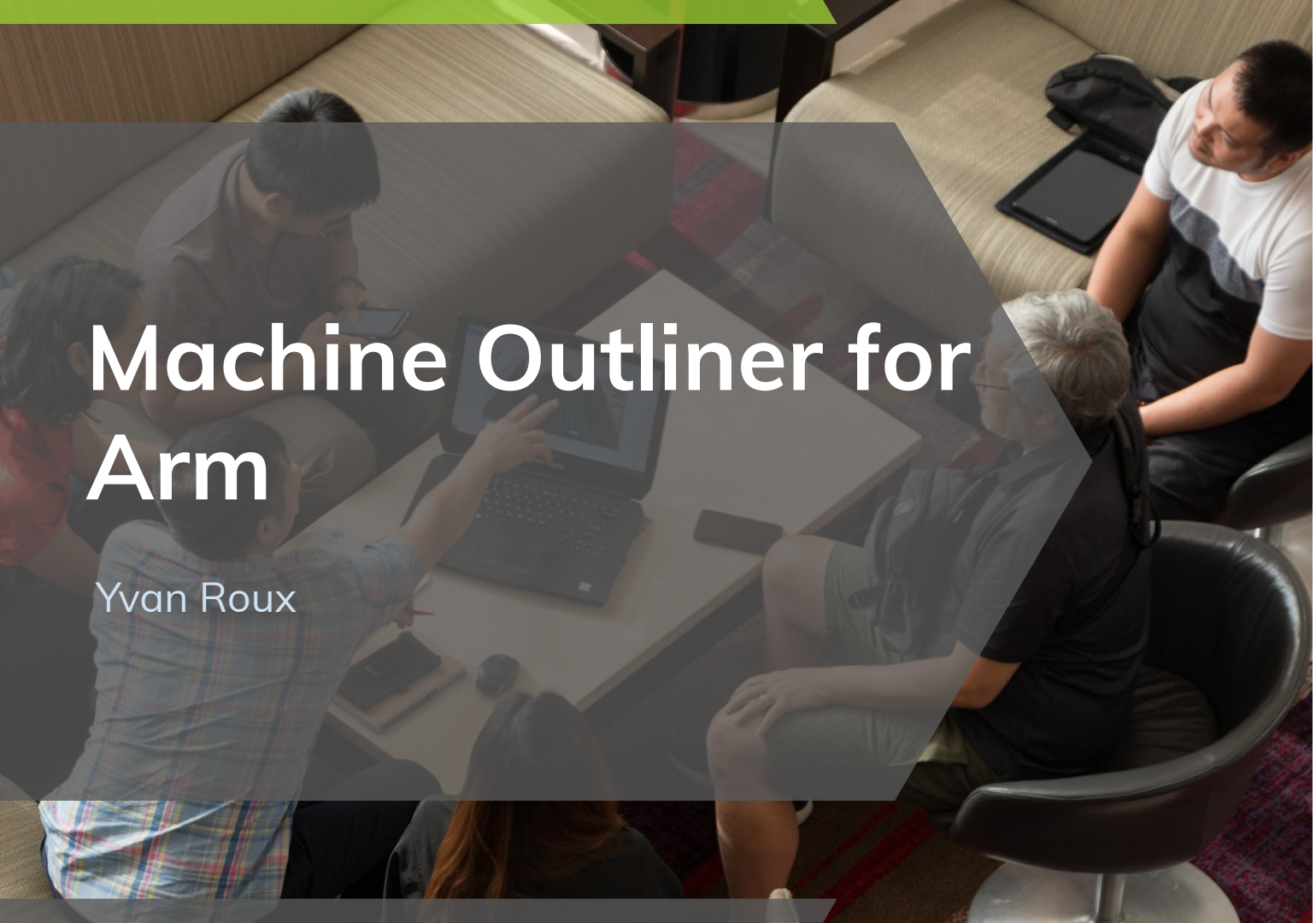
Benchmark - mbed-os examples

Code size change, compared to -Oz -flto -fvisibility=hidden



Future work

- Commit the patch (in review)
- Turn on by default
- ThinLTO - currently requires full LTO
- Dead RTTI elimination



Machine Outliner for Arm

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LLVM Machine Outliner

- Code-size reduction pass
- Replacing repeated sequences of code by calls to equivalent functions
- Introduced by Apple for AArch64 and X86 in 2017

Example

```
foo:
        movw    r0, :lower16:a
        movt    r0, :upper16:a
        ldr     r0, [r0]
        movw    r1, :lower16:b
        movt    r1, :upper16:b
        ldr     r1, [r1]
        add     r0, r0, r1
        movw    r1, :lower16:c
        movt    r1, :upper16:c
        ldr     r1, [r1]
        add     r0, r0, r1
        movw    r1, :lower16:d
        movt    r1, :upper16:d
        ldr     r1, [r1]
        add     r0, r0, r1
        bx      lr
```

```
bar:
        movw    r0, :lower16:a
        movt    r0, :upper16:a
        ldr     r0, [r0]
        movw    r1, :lower16:b
        movt    r1, :upper16:b
        ldr     r1, [r1]
        add     r0, r0, r1
        movw    r1, :lower16:c
        movt    r1, :upper16:c
        ldr     r1, [r1]
        add     r0, r0, r1
        movw    r1, :lower16:d
        movt    r1, :upper16:d
        ldr     r1, [r1]
        sub     r0, r0, r1
        bx      lr
```

Example

```
foo:
        movw    r0, :lower16:a
        movt    r0, :upper16:a
        ldr     r0, [r0]
        movw    r1, :lower16:b
        movt    r1, :upper16:b
        ldr     r1, [r1]
        add     r0, r0, r1
        movw    r1, :lower16:c
        movt    r1, :upper16:c
        ldr     r1, [r1]
        add     r0, r0, r1
        movw    r1, :lower16:d
        movt    r1, :upper16:d
        ldr     r1, [r1]
        add     r0, r0, r1
        bx      lr
```

```
bar:
        movw    r0, :lower16:a
        movt    r0, :upper16:a
        ldr     r0, [r0]
        movw    r1, :lower16:b
        movt    r1, :upper16:b
        ldr     r1, [r1]
        add     r0, r0, r1
        movw    r1, :lower16:c
        movt    r1, :upper16:c
        ldr     r1, [r1]
        add     r0, r0, r1
        movw    r1, :lower16:d
        movt    r1, :upper16:d
        ldr     r1, [r1]
        sub     r0, r0, r1
        bx      lr
```

Example

```
foo:
        mov     r2, lr
        bl      OUTLINED_FUNCTION_0
        mov     lr, r2
        add     r0, r0, r1
        bx      lr

bar:
        mov     r2, lr
        bl      OUTLINED_FUNCTION_0
        mov     lr, r2
        sub     r0, r0, r1
        bx      lr
```

```
OUTLINED_FUNCTION_0:
        movw    r0, :lower16:a
        movt    r0, :upper16:a
        ldr     r0, [r0]
        movw    r1, :lower16:b
        movt    r1, :upper16:b
        ldr     r1, [r1]
        add     r0, r0, r1
        movw    r1, :lower16:c
        movt    r1, :upper16:c
        ldr     r1, [r1]
        add     r0, r0, r1
        movw    r1, :lower16:d
        movt    r1, :upper16:d
        ldr     r1, [r1]
        bx      lr
```

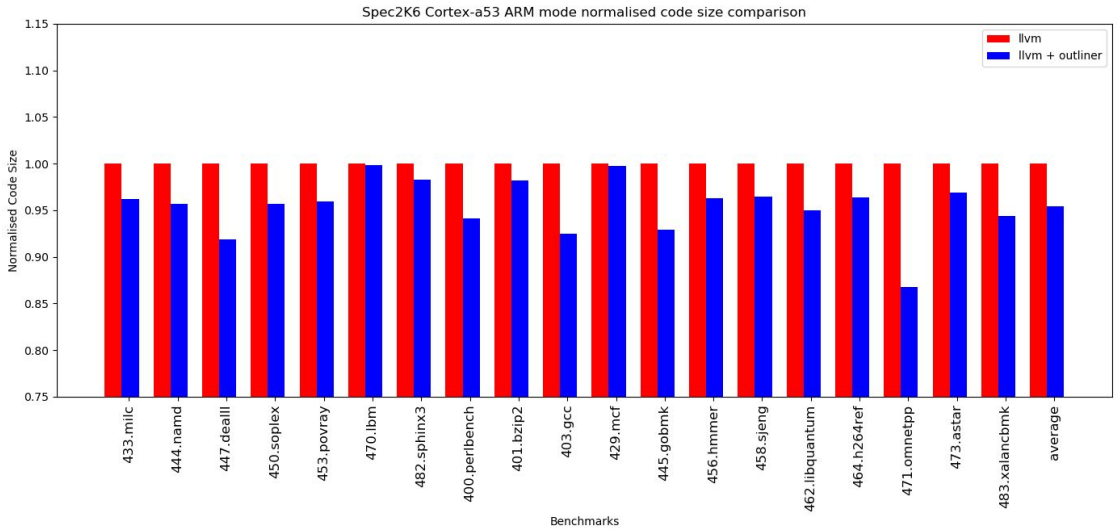
28 bytes saved in this case

Non-Outlinable cases

- Conditional execution, IT blocks
- IP register or Condition code usage
- Instructions with PC dependent behavior
- Stack operations

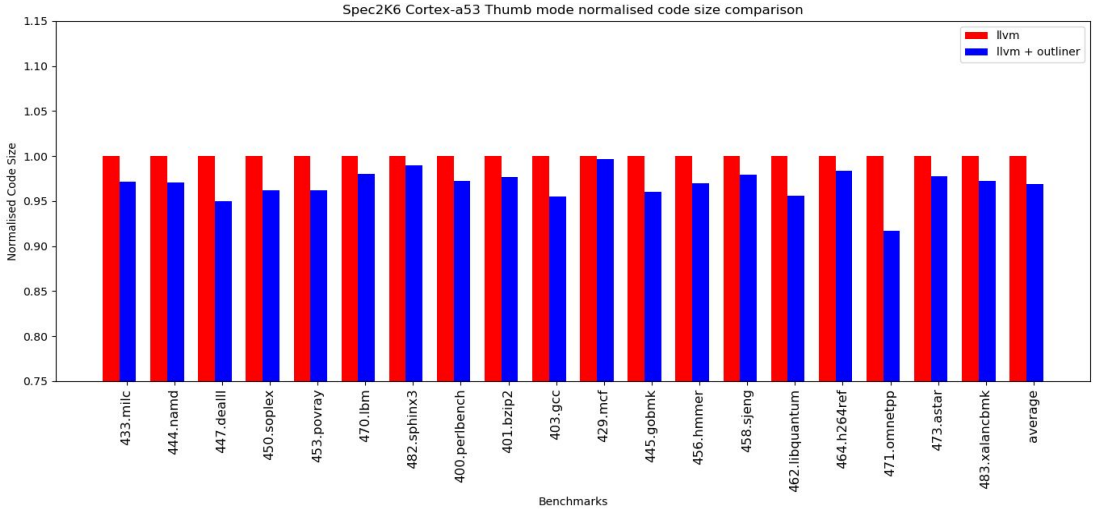
Spec2K6 Cortex-A53 ARM mode results normalized to LLVM Oz

- Code size is 4.8% smaller on average with Machine Outliner turned on

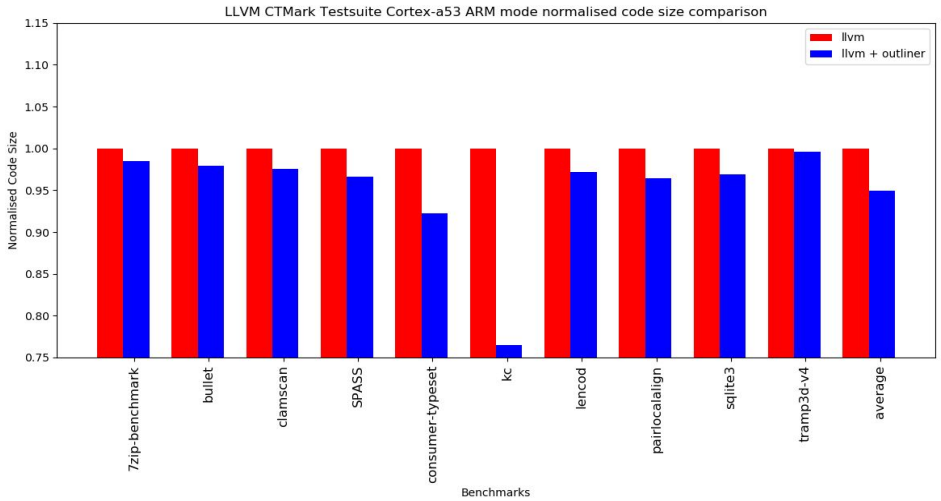


Spec2K6 Cortex-A53 Thumb mode results normalized to LLVM Oz

- Code size is 3.3% smaller on average with Machine Outliner turned on for Thumb

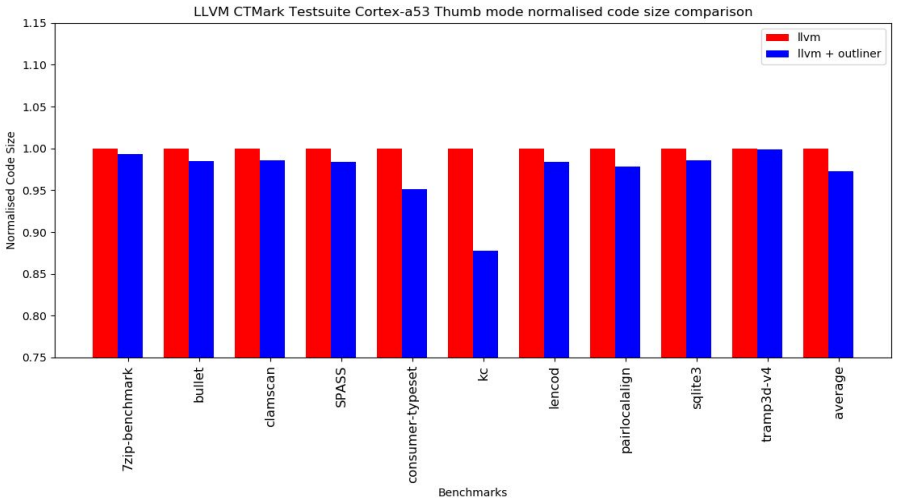


LLVM CTMark Testsuite Cortex-A53 ARM mode results normalized to LLVM Oz



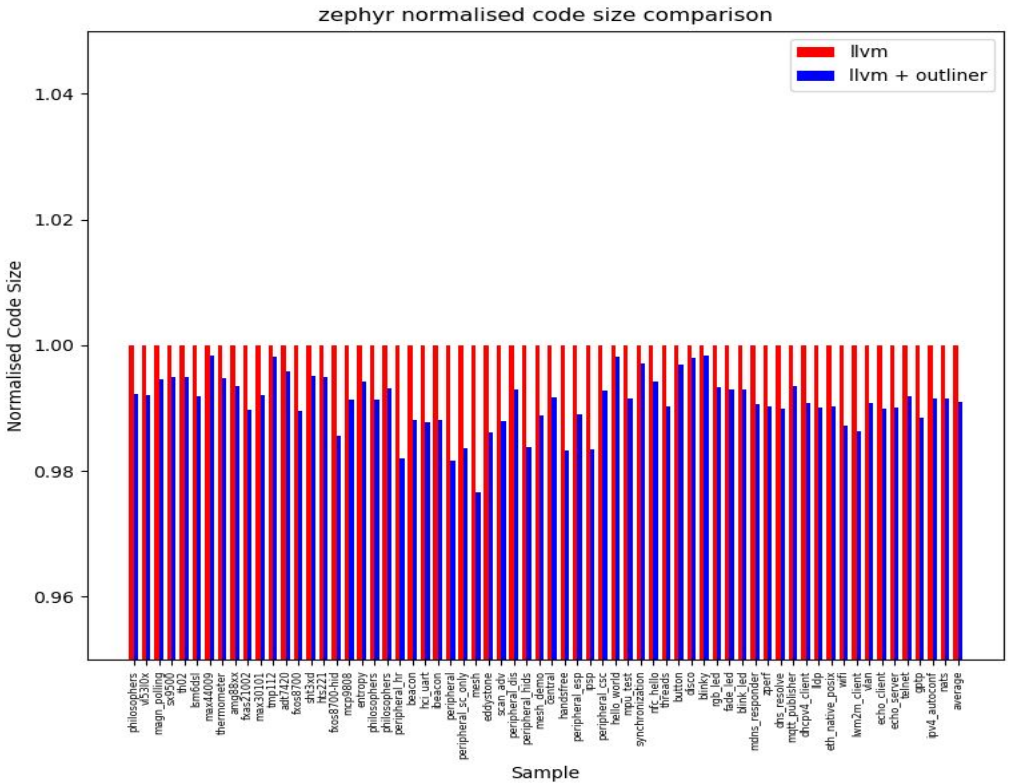
- Code size is 5.3% smaller on average with Machine Outliner turned on

LLVM CTMark Testsuite Cortex-A53 Thumb mode results normalized to LLVM Oz



- Code size is 2.8% smaller on average with Machine Outliner turned on

Zephyr Cortex-M4 results normalized to LLVM Oz



- Code size is 1.1% smaller on average with Machine Outliner turned on
- It brings LLVM to parity with GCC

Summary

- Clang is slightly worse than GCC for code-size on the Zephyr code-base.
- Clang can be substantially better for DSP/Floating point code.
- Forthcoming size optimizations to Clang such as VFE and the outliner will help to close the gap.

Thank you

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Backup, measuring code-size

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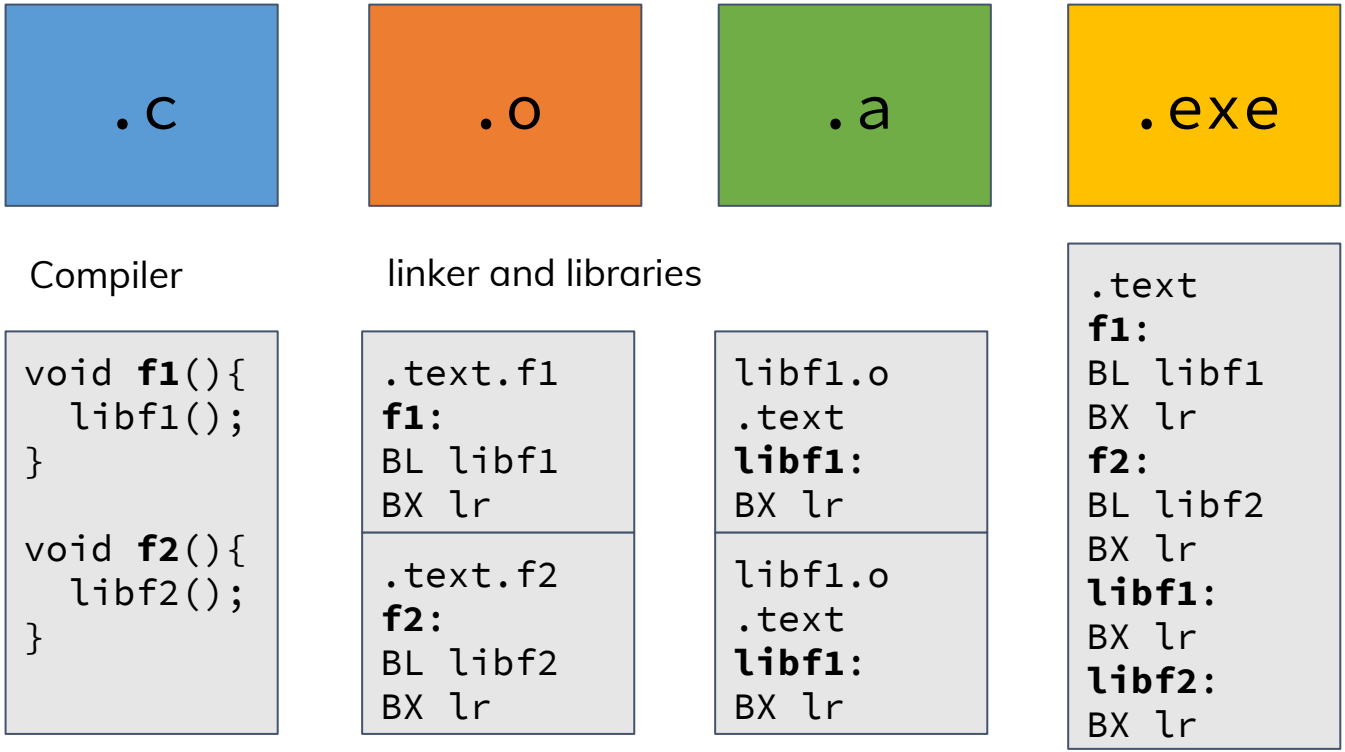
Factors influencing the code size of a program



Code generated by compiler.

Code from static libraries added at link time.

Linker optimizations such as garbage collection depend on section layout.

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Measuring code size in an ELF file

```
int global_variable = 10;

int func(void) {
    return global_variable;
}
```

- ELF sections can be read with readelf --sections
- ELF symbols can be read with readelf --symbols
- The size of a section includes all functions defined within
- Compiler gives symbol defining a size that can give the code size of a function

```
[Nr] Name              Type            Addr     Off    Size   ES Flg Lk Inf Al
...
[ 3] .text.func        PROGBITS        00000000 000034 000010 00  AX  0   0  4
...
[ 7] .data.global_vari PROGBITS        00000000 00004c 000004 00  WA  0   0  4
```

```
Num:    Value  Size Type    Bind   Vis      Ndx Name
4: 00000000    16 FUNC    GLOBAL DEFAULT    3 func
5: 00000000     4 OBJECT  GLOBAL DEFAULT    7 global_variable
```

Compiler output is not enough, comdat groups

```
// May be instantiated in other
// files.
template<typename T>
T add(T a, T b) {
    return a+b;
}
// Take address of function
// to force definition
template<typename T>
using fptr = T (*) (T, T);
fptr<int> fpint = &add<int>;

int func(int a, int b) {
    return add(1, 2);
}
```

```
.text
_Z4funcii:
ADD r0, r1, r0
BX lr
```

```
.group
SHT_GROUP
GRP_COMDAT
.text._Z3addIiET_S0_S0_
```

```
.text._Z3addIiET_S0_S0_
_Z4funcii:
ADD r0, r1, r0
BX lr
```

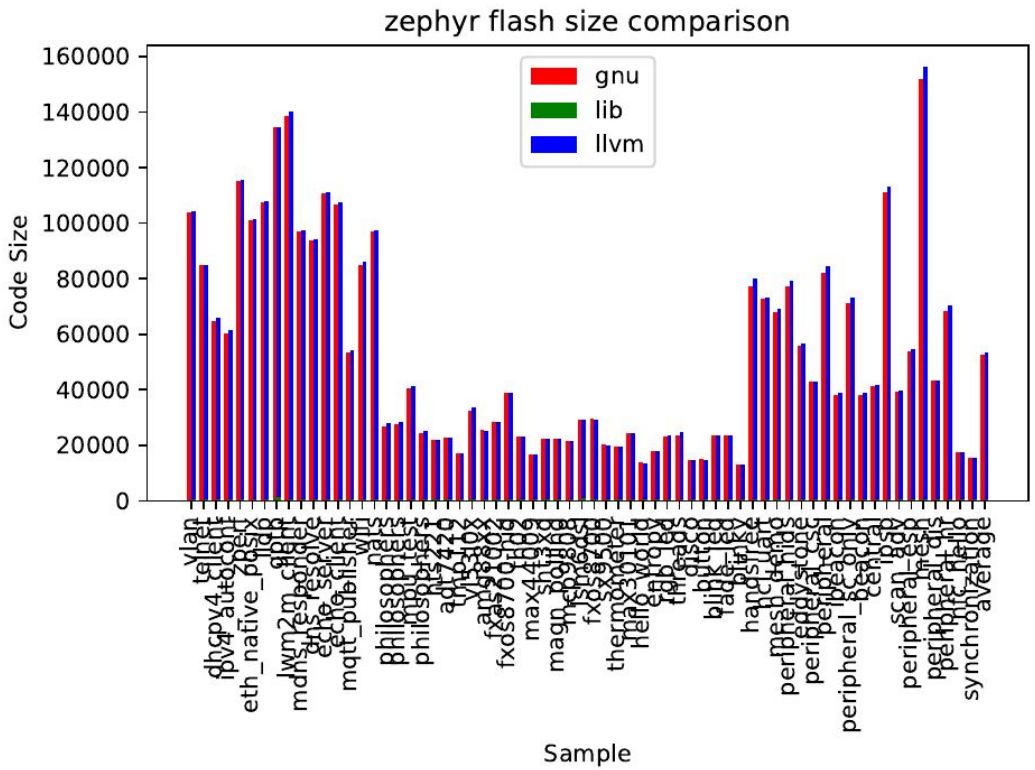
Compiler output is not enough, library calls

```c
#include <string.h>

#define SIZE 12

int globvar1[SIZE];
int globvar2[SIZE];

void func() {
    memcpy(&globvar1,
           &globvar2,
           sizeof(globvar1));
}
```

```
// At SIZE 12 memcpy inlined
LDM  ip!, {r0, r2, r3, r4, r5, lr}
STM  r1!, {r0, r2, r3, r4, r5, lr}
LDM  ip, {r0, r2, r3, r4, r5, lr}
STM  r1, {r0, r2, r3, r4, r5, lr}
```

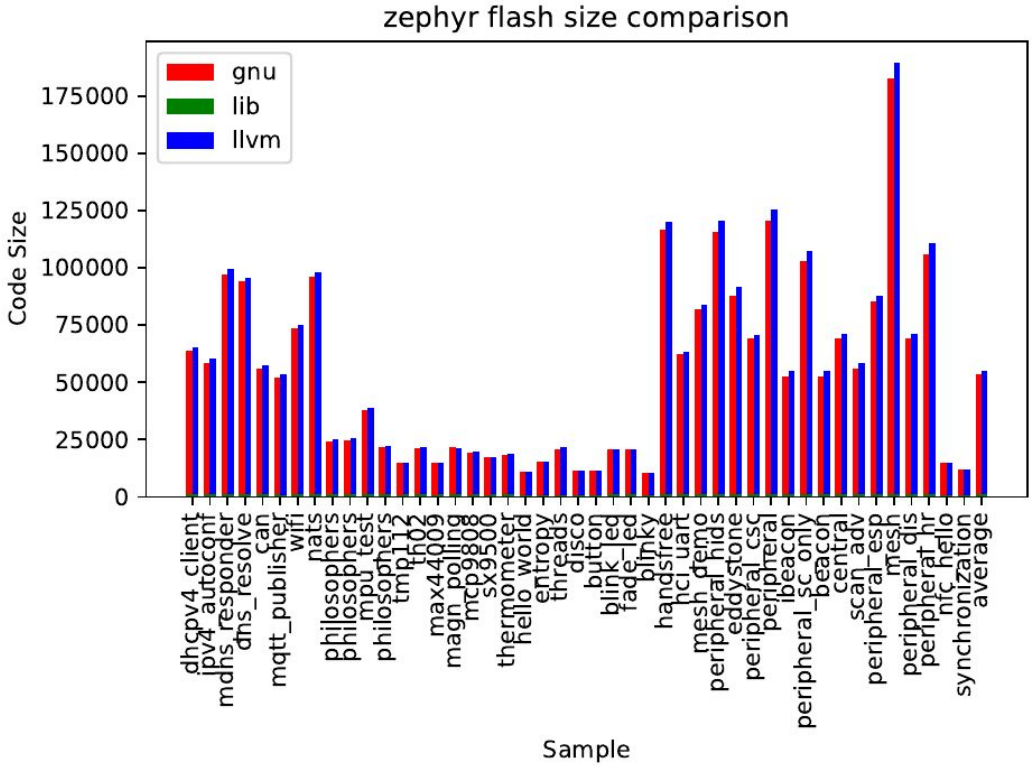
```
// At SIZE 120 memcpy called, smaller
// code size in object, but the
// executable will include size of
// __aeabi_memcpy4
BL   0 <__aeabi_memcpy4>
```

Cortex-M4 non-normalized results



- Flash size includes code and non ZI data
- Library size so small it is not visible
- Cortex-M4 has the most supported samples
- Total LLVM Size 3462456
- Total GCC Size 3424092
- LLVM is 1.1% larger

Cortex-M0 non-normalized results



- Cortex-M0 has fewer supported samples
- Total LLVM Size 2474544
- Total GCC Size 2404132
- LLVM is 2.8% larger

CMSIS DSP Cortex-M4f