Linker Code Size Optimization for Native Mobile Applications

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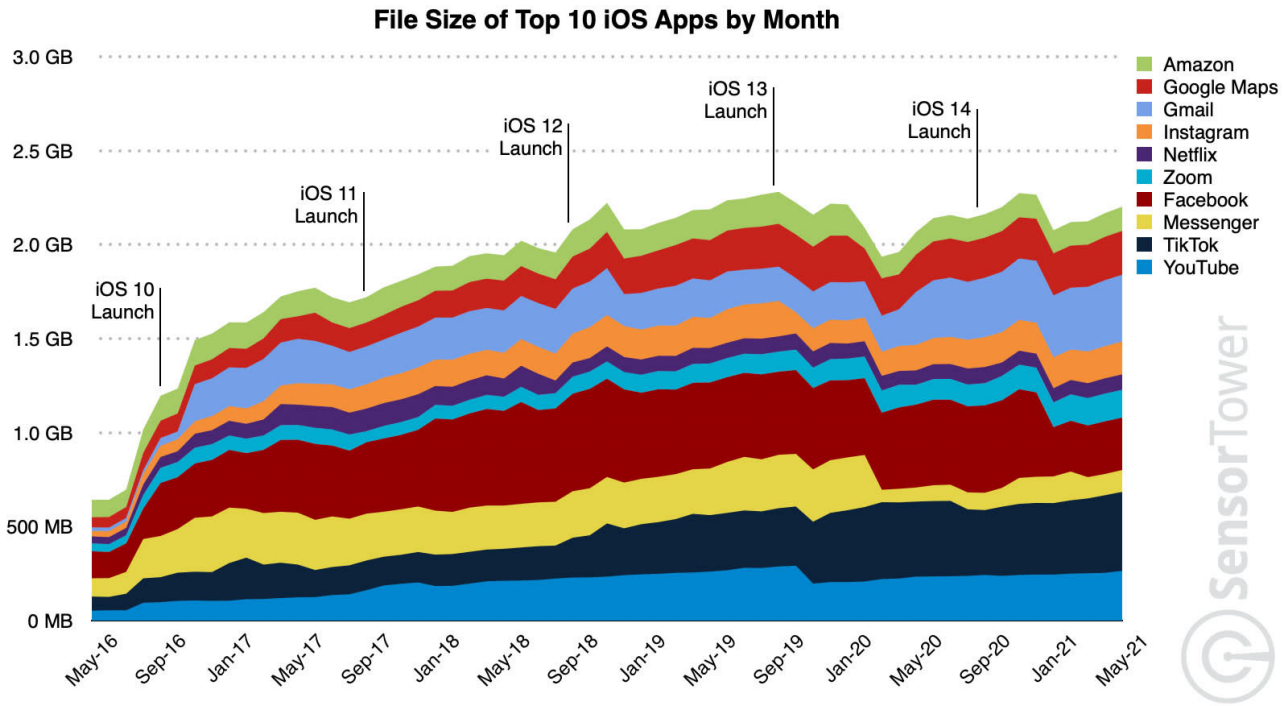
Impact of Code Size on Mobile Applications

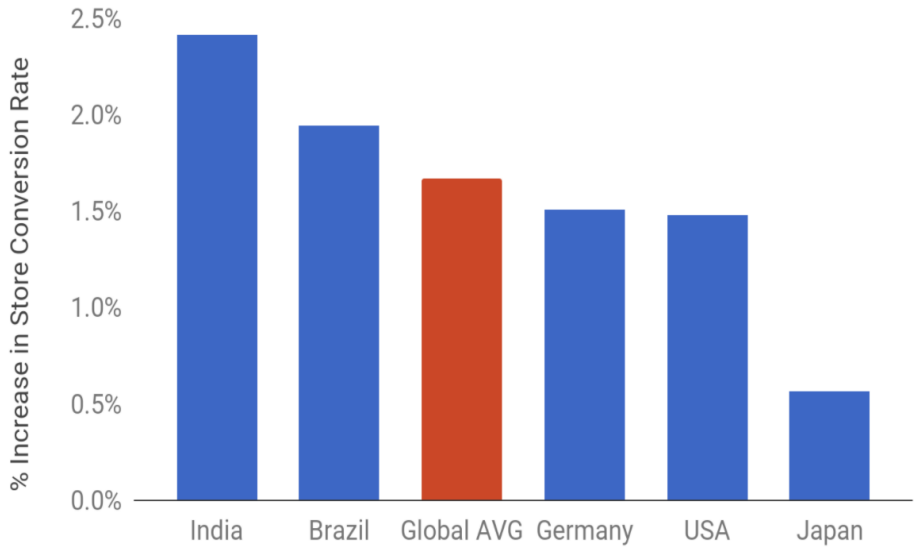
More features → larger apps



Credit: SensorTower

Larger apps decrease user engagement

Install conversion rate increase per 10MB decrease in APK size by market



Credit: Sam Tolomei, Google, 2017

Today's topic: transformations to reduce code size for mobile apps

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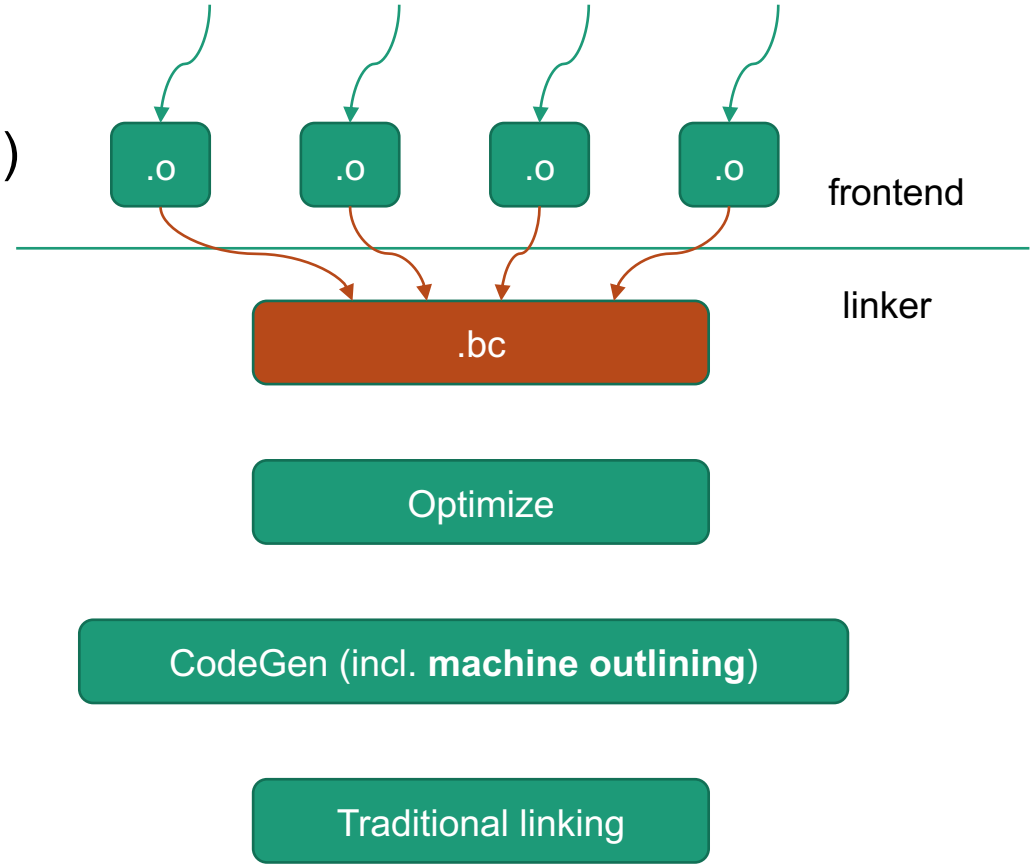
State of the Art Approaches

- Key is to enable **global** size optimization
  - Commonly through link-time optimization (LTO) + machine outlining
  - Monolithic LTO based approach [1]



~3x slowdown vs. default pipeline!

[1] Chabbi, Lin, and Barik, CGO'21

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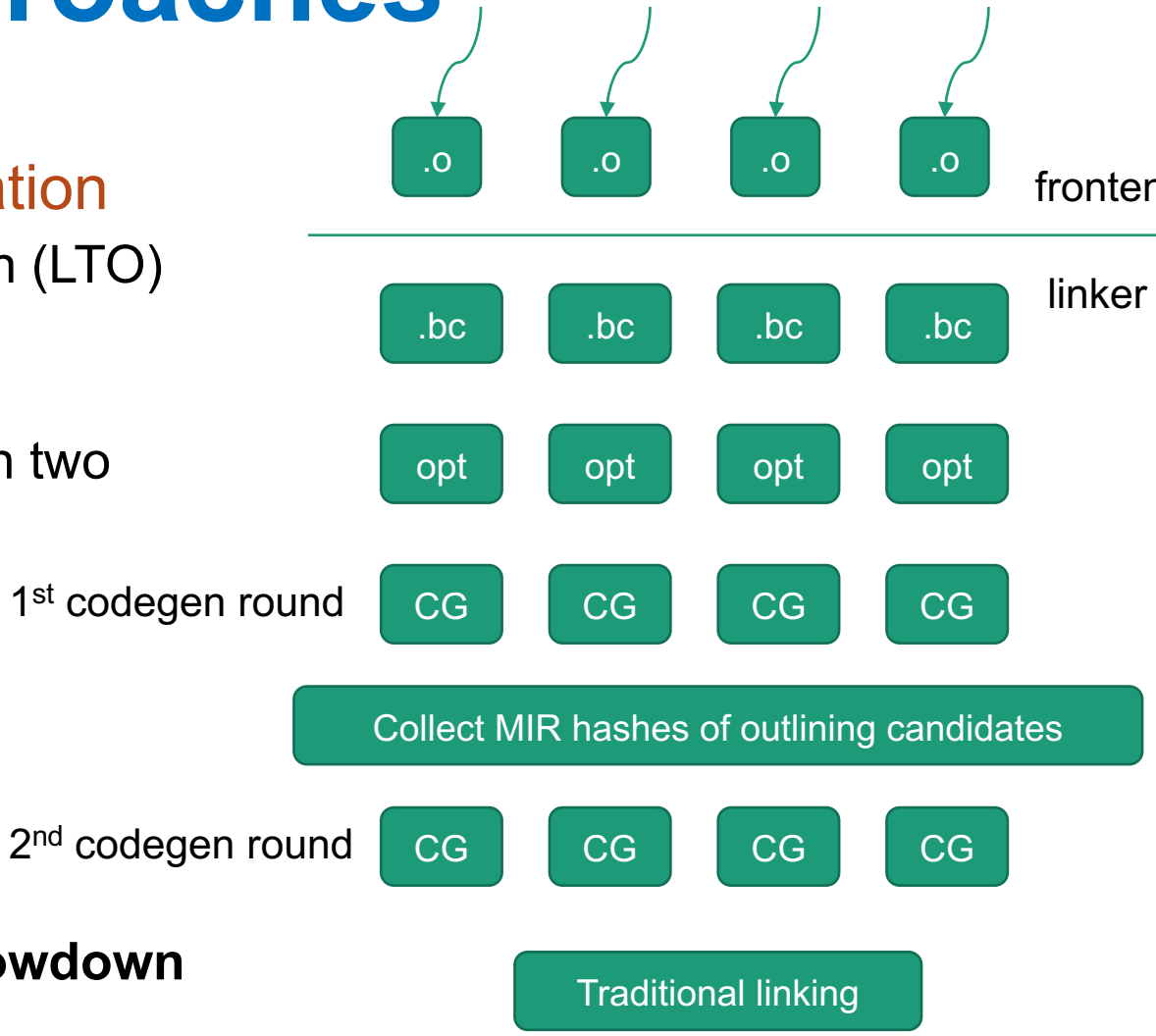
State of the Art Approaches

- Key is to enable **global** size optimization
  - Commonly through link-time optimization (LTO) + machine outlining
  - Monolithic LTO based approach [1]
  - Size optimization based on thin LTO with two codegen rounds [2]



~40% slowdown

[1] Chabbi, Lin, and Barik, CGO'21
[2] Lee, Hoag and Tillmann, CC'22

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Some Additional Challenges…

~50% code is from binary in our builds

	Compatible with existing build pipeline	Small build time penalty	Optimizes binary form libraries
Monolithic LTO			
Size optimizing thin LTO			

New approach?

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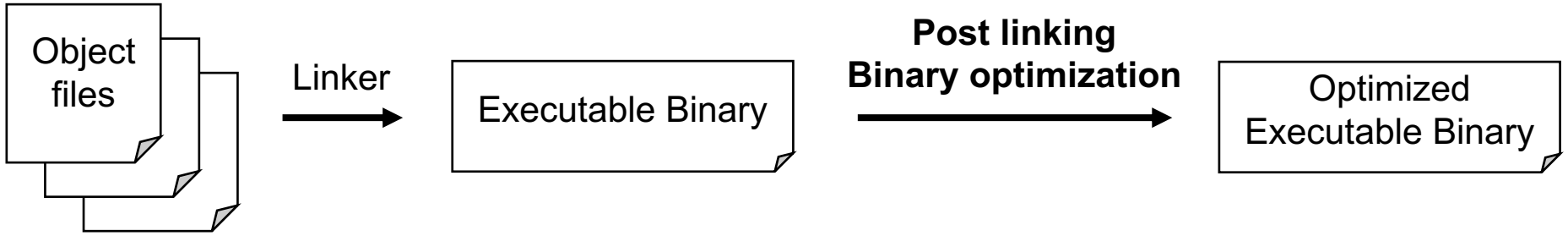
Proposal: Build an Optimizing Linker

- Existing linkers are good at symbol manipulation
  - Dead symbol stripping, function deduplication, etc.
  - But no sophisticated **code transformations inside functions**
- Optimizing code size in linker:

Compatible with existing build pipeline	Small build time penalty	Optimizes binary form libraries
✓ -fuse-ld=myld	✓ lightweight & specialized linker passes	✓

vs. Post Linking Optimization

Snippet of a post linking optimization pipeline:



Linker Opt.

- One implementation per linker
- Easy integration into build pipeline

Post Linking Opt.

- Independent of specific linker
- Additional step in the build pipeline

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Rest of the Talk

- An infrastructure for linker code size optimization
  - Implemented on top of Apple's ld64 linker
    - Looking into lld porting
  - Targeting ARM64 architecture
- >10% binary size reduction in our iOS apps
- <10% end-to-end build time overhead

Key Components

Utilities & Analyses

- Instruction decoder
- Sequence hashing

Code transformations

- Sequence outlining
- Safe ICF

Non-code section updates

- Exception table
- Debug info
- etc.

Prepare for Outlining

- Decode the instruction stream

```
f45c: sub sp, sp, #48
f460: stp x20, x19, [sp, #16]
f464: stp x29, x30, [sp, #32]
f468: add x29, sp, #32
f46c: adrp  x8, 44223
f470: ldr x8, [x8, #3288]
f474: stp x0, x8, [sp]
f478: adrp  x8, 55266
f47c: ldr x1, [x8, #376]
f480: mov x0, sp
f484: bl  _objc_msgSendSuper2
f488: mov x19, x0
f48c: cbz x0, 0xf4b4
f490: adrp  x8, 44163
f494: ldr x0, [x8, #256]
f498: adrp  x8, 55295
f49c: ldr x1, [x8, #2976]
f4a0: bl  _objc_msgSend
f4a4: ldr x8, [x19, #8]
f4a8: str x0, [x19, #8]
f4ac: mov x0, x8
f4b0: bl  _objc_release
f4b4: mov x0, x19
f4b8: ldp x29, x30, [sp, #32]
f4bc: ldp x20, x19, [sp, #16]
f4c0: add sp, sp, #48
f4c4: ret
```

Prepare for Outlining

- Mark “pivot” instructions
  - Instructions that are not suitable for outlining
  - Targets of branch instructions
  - Exception table range endpoints

```
f45c: sub sp, sp, #48
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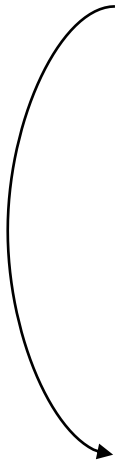
```



pivot instructions

0xf4b4
…
….

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Find Outlining Candidates

- Hash sequences across all functions
  - Skip pivot instructions

Example: len = 5

h1

```
f45c: sub sp, sp, #48
f460: stp x20, x19, [sp, #16]
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f468: add x29, sp, #32
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f4ac: mov x0, x8
f4b0: bl  _objc_release
f4b4: mov x0, x19
f4b8: ldp x29, x30, [sp, #32]
f4bc: ldp x20, x19, [sp, #16]
f4c0: add sp, sp, #48
f4c4: ret
```

hash	freq	len
h1	1	5

pivot instructions

0xf4b4
…
….

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```
f45c: sub sp, sp, #48
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f478: adrp  x8, 55266
f47c: ldr x1, [x8, #376]
f480: mov x0, sp
f484: bl  _objc_msgSendSuper2
f488: mov x19, x0
f48c: cbz x0, 0xf4b4
f490: adrp  x8, 44163
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f498: adrp  x8, 55295
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f4a8: str x0, [x19, #8]
f4ac: mov x0, x8
f4b0: bl  _objc_release
f4b4: mov x0, x19
f4b8: ldp x29, x30, [sp, #32]
f4bc: ldp x20, x19, [sp, #16]
f4c0: add sp, sp, #48
f4c4: ret
```

h2

hash	freq	len
h1	1	5
h2	1	5

pivot instructions

0xf4b4
…
….

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Find Outlining Candidates

- Hash sequences across all functions
  - Skip pivot instructions

Linear scan-based algorithm:

- Easy to implement & debug
- Linear time complexity (under a max sequence length)
- Exhaustive for a given *len*

Example: len = 5

h3

```
f45c: sub sp, sp, #48
f460: stp x20, x19, [sp, #16]
f464: stp x29, x30, [sp, #32]
f468: add x29, sp, #32
f46c: adrp  x8, 44223
f470: ldr x8, [x8, #3288]
f474: stp x0, x8, [sp]
...
f478: adrp  x8, 55266
f47c: ldr x1, [x8, #376]
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f4a8: str x0, [x19, #8]
f4ac: mov x0, x8
f4b0: bl  _objc_release
f4b4: mov x0, x19
f4b8: ldp x29, x30, [sp, #32]
f4bc: ldp x20, x19, [sp, #16]
f4c0: add sp, sp, #48
f4c4: ret
```

hash	freq	len
h1	1	5
h2	1	5
h3	1	5

pivot instructions

0xf4b4
…
….

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Find Outlining Candidates

- Sort candidates by profitability

hash	freq	len
h1	4	4
h2	1	4
h3	8	4
…	…	…
h_n	3	8
…	…	…

Sort by profitability →

hash	freq	len
h15432	38	5
h80	12	8
h912	20	4
…	…	…
h2	1	4
…	…	…

Profitable

Not profitable

```
f45c: sub sp, sp, #48
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f464: stp x29, x30, [sp, #32]
f468: add x29, sp, #32
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Outline Transformation

Relocations are handled automatically by downstream linker step

```
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f4b4: mov x0, x19
f4b8: ldp x29, x30, [sp, #32]
f4bc: ldp x20, x19, [sp, #16]
f4c0: add sp, sp, #48
f4c4: ret
```

```
f0c0: stp x29, x30, [sp, #-16]
f0c4: bl  OUTLINED_PROLOG_71

f0c8: sub sp, sp, #48
f0cc: adrp  x8, 38502
f0d0: ldr x8, [x8, #736]
f0d4: bl  LD_OUTLINED_15371

f0d8: mov x19, x0
f0dc: cbz x0, 0xf0f0
f0e0: adrp  x8, 38439
f0e4: ldr x0, [x8, #2160]
f0e8: bl  LD_OUTLINED_65726

f0ec: bl  LD_OUTLINED_33189

f0f0: mov x0, x19
f0f4: add sp, sp, #48
f0f8: b OUTLINED_EPILOG_311
```

Update cbz's relative offset

```
OUTLINED_PROLOG_71:
 stp  x20, x19, [sp, #-32]
 sub  x29, sp, #16
 ret

LD_OUTLINED_15371:
 stp  x0, x8, [sp]
 adrp x8, 49429
 ldr  x1, [x8, #2752]
 mov  x0, sp
 b  _objc_msgSendSuper2

LD_OUTLINED_65726:
 adrp  x8, 49197
 ldr x1, [x8, #3000]
 b _objc_msgSend

LD_OUTLINED_33189:
 ldr x8, [x19, #8]
 str x0, [x19, #8]
 mov x0, x8
 b _objc_release

OUTLINED_EPILOG_3
11:
 ldp x29, x30, [sp, #-16]
 ldp x20, x19, [sp, #-32]
 ret
```

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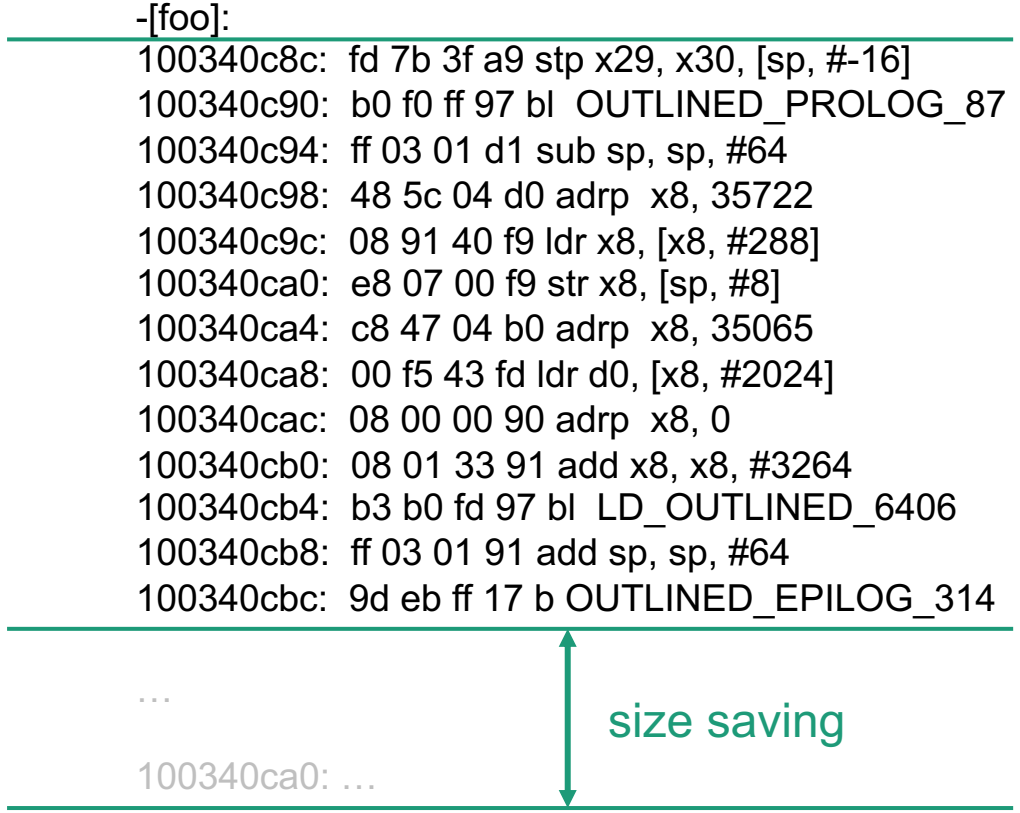
Update Non-Code Sections

- Fix content of sections that rely on instruction addresses
  - __debug_info
  - __debug_line
  - __gcc_except_table



DWARF debugging information entry

DW_TAG_subprogram
DW_AT_low_pc (0x0000000100340c8c)
DW_AT_high_pc (0x0000000100340ca0)
…

(0x0000000100340cbc)

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Safe Identical Code Folding

- Outlining reduces redundancies at instruction sequence level
- ICF removes redundancies at function level
  - Mature pass in lld
- We enhanced the ICF pass in ld64
  - More aggressive size opt
  - Improved compile time
  - Made it safe under pointer comparisons
    - Use redirection instead of direct replacement
  - More details offline

Implementation & Experimental Setup

- ~3500 lines of C++ code as ld64 passes
- Benchmarks
  - Three commercial iOS apps
    1. News recommendation
    2. Short video hosting and sharing
    3. Enterprise collaboration client
  - mixture of Objective-C, Swift, C++, Rust
    - 1 to 2 million functions per app
- Build machine
  - 2.6 GHz, 6-core CPU, 64 GB RAM

ld64 pass pipeline

Passes/Optimizations

- Objective-C optimizations
- Stub/GOT/TLV generation
- **Linker outlining**
- Order atoms
- **Safe identical code folding**
- Branch island/shim generation
- DTrace probe processing
- Compact unwind encoding

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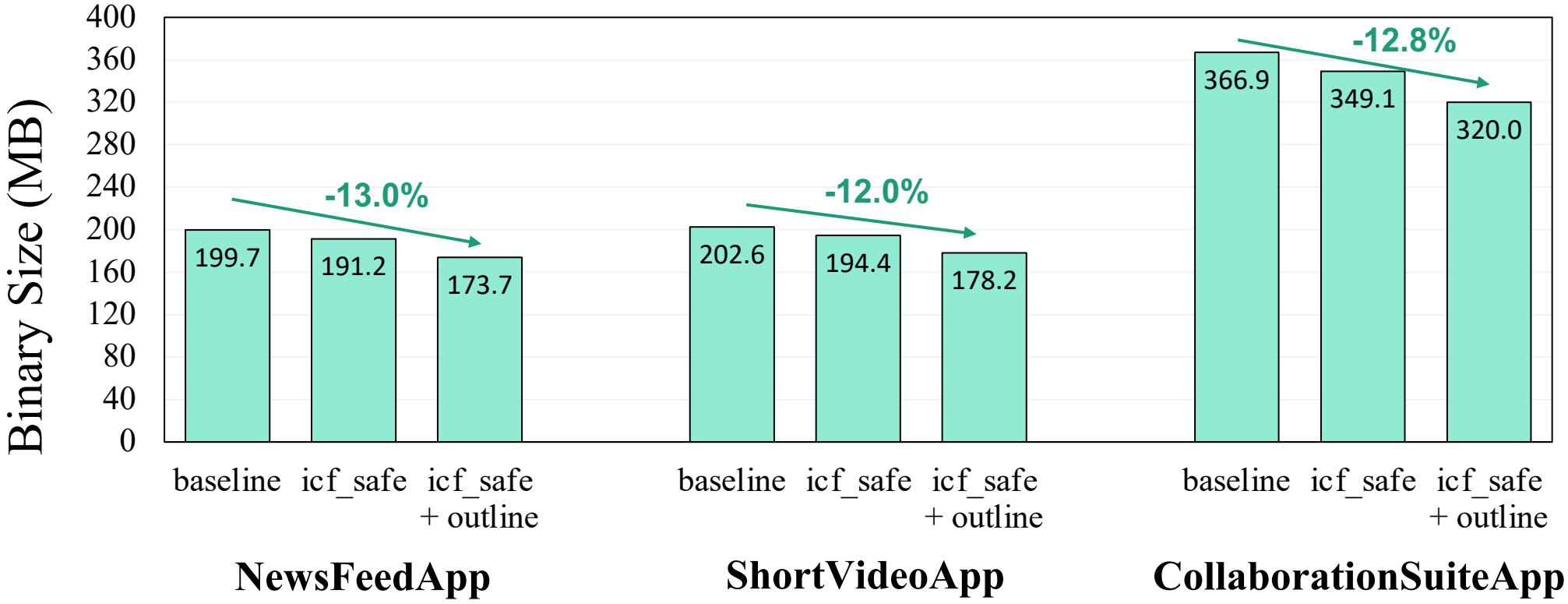
Size Reduction



No noticeable performance degradations from production data

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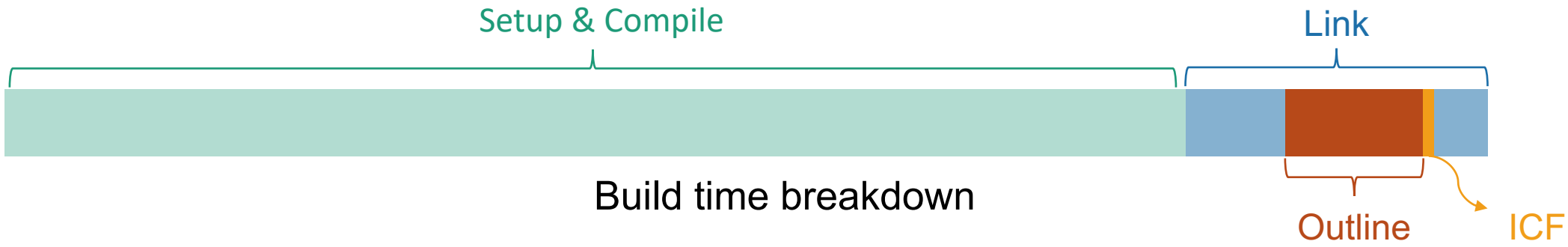
Build Time Comparisons

- Linker outline + ICF overhead
  - Doubles the link time
  - <10% overhead overall

	Wall Time
icf_safe pass	17s
outline pass	2m15s
Total link time	5m23s
Total build time	46m31s



Build time breakdown

- Comparison
  - Monolithic LTO increases link time by > 2 hours for our apps

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Summary

- We presented a framework for native code size optimization within the linker
  - Minimal change to build pipeline
  - Small build time overhead
  - Optimizes binary libraries

- arXiv preprint
  - arxiv.org/abs/2210.07311v1

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