Improving Machine Outliner for ThinLTO

(Global Machine Outliner + Frame Code Outliner)

Facebook

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The Machine Outliner Today

- Machine outliner in LLVM significantly reduces code size
  - Works quite well with the whole program mode (LTO).
  - LLVM-TestSuite/CTMark (arm64/-Oz) up to 11% on average
- Under **ThinLTO**, its effectiveness drops significantly
  - Operates within each **module scope**
  - **Misses all cross-module outlining opportunities**
  - **Identical outlined functions** in cross-modules **not deduplicated**
- Frame-layout code tend to not get outlined
  - Generated frame-layout code is irregular
  - Typically optimized for performance

No Outliner

a.c:

```
int f1(int x) {
  // ...more code...
  return x * 128 + 77;
}
int f2(int x) {
  // ...more code...
  return x * 128 + 77;
}
```

b.c:

```
int g(int x) {
  // ...more code...
  return x * 128 + 77;
}
```

Machine Outliner

LTO

```
int f1(int x) {
  // ...more code...
  return __outlined(x);
}
int f2(int x) {
  // ...more code...
  return __outlined(x);
}
int g(int x) {
  // ...more code...
  return __outlined(x);
}
int __outlined(int x) {
  return x * 128 + 77;
}
```

ThinLTO

```
int f1(int x) {
  // ...more code...
  return __outlined(x);
}
int f2(int x) {
  // ...more code...
  return __outlined(x);
}
int __outlined(int x) {
  return x * 128 + 77;
}
```

```
int g(int x) {
  // ...more code...
  return x * 128 + 77;
}
```

Typical (Irregular) Frame Code for Speed

- Optimized to reduce # of instructions and micro-operations
  - SP adjustment once for CSR and/or local
- Instructions for handling LR (X30) often comes late in the prologue or early in the epilogue
  - Blocker for outliner

(Prologue)

```
stp x22, x21, [sp, #-48]!
stp x20, x19, [sp, #16]
stp x29, x30, [sp, #32]  // Can't outline
add x29, sp, #32
...
```

(Epilogue)

```
ldp x29, x30, [sp, #32]  // Can't outline
ldp x20, x19, [sp, #16]
ldp x22, x11, [sp], #48
ret
```

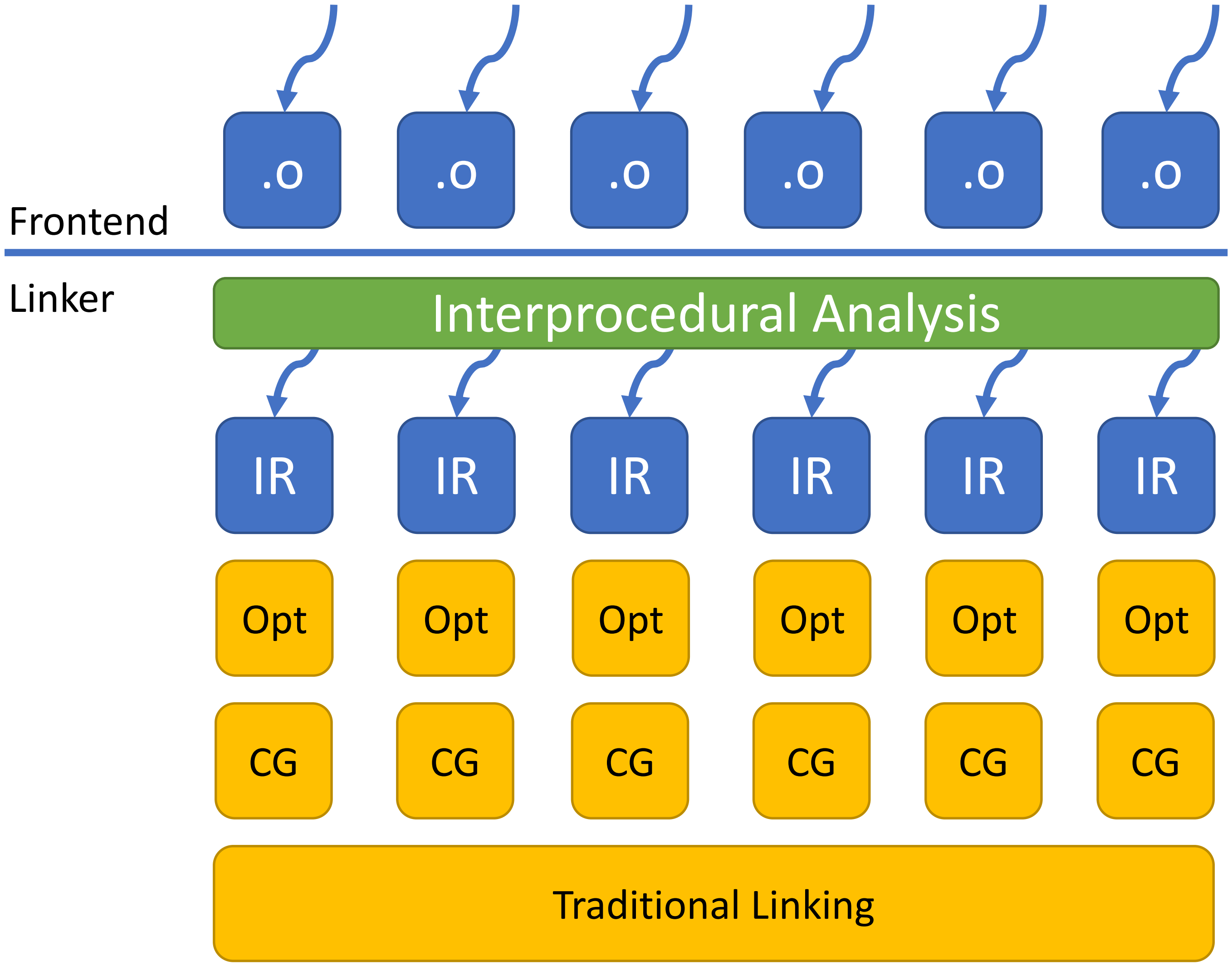
Text Size Reduction with Machine Outliner for ThinLTO vs. LTO

- LLVM-TestSuite/CTMark (arm64/-Oz)
- ThinLTO outliners saves 8% code size while LTO does 11% code size.

Proposed Improvements

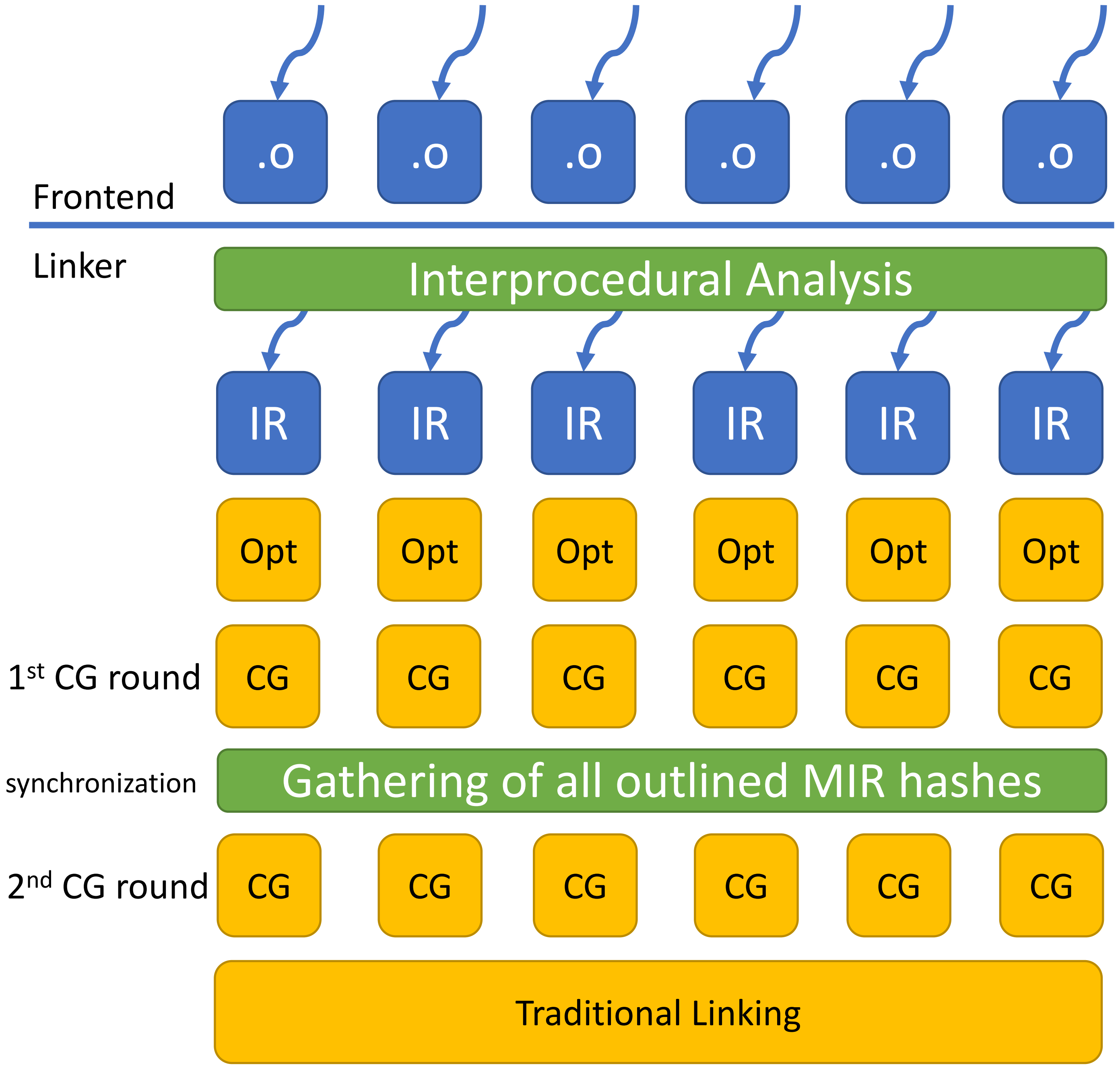
- Global Outliner in ThinLTO
  - Capture (stable) hashes of outlined functions for all modules
  - Make more outlines (but not folded) if a same hash sequence exists.
  - Realize code-size reduction via linker’s deduplication
- Frame code optimizations
  - Make frame code more homogeneous
  - Custom-outline frame code

Global Outliner in ThinLTO



Recall: ThinLTO

- Frontend compiler .o files in parallel
- After interprocedural analysis, runs in parallel for each module:
  - Opt (HIR)
    - Inlining/Optimizer
  - CodeGen (MIR)
    - RA/Machine Outliner
- Finally, traditional linking combines results



2-round CodeGen!

- Serialize IR just before 1st CG
- Deserialize IR before 2nd CG

<u>1st round:</u>

- Gather MIR hashes of outlined functions

<u>2nd round:</u>

- (Optimistically) outline more candidates that match MIR hashes

<u>Linking:</u>

- Fold outlined functions across modules

Build a Global Prefix Tree in First Round

- Recall: Machine outliner uses a **suffix tree** to find sequences occurring at least 2 times
- For each outlined function (within a module),
  - Hash the machine instruction using a stable hash below
  - Insert the sequence of hashes into a **global prefix tree**
- **Stable machine instruction hash (valid cross-modules)**
  - 64-bit, using stronger hash function
  - do not hash pointers, but deep meaningful value representations, e.g. names
  - hashes are *quite exact* across modules and (de)serializable.

Global prefix tree: Building (in First Round CG)

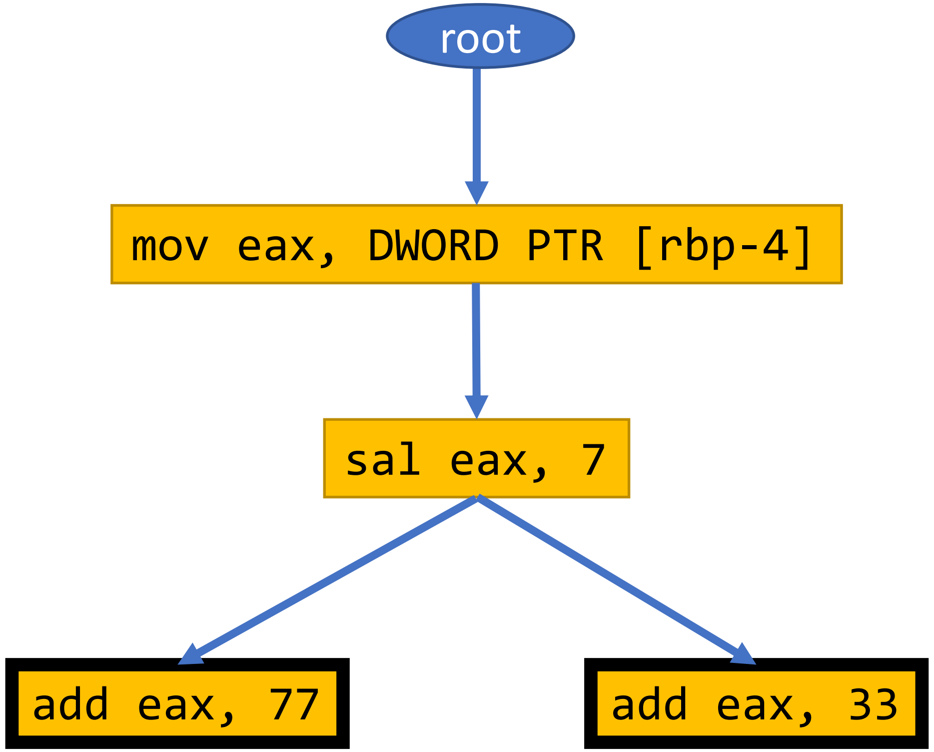
a.c:

```
int __outlined1(int x) {
  return x * 128 + 77;
}
```

```
mov eax, DWORD PTR [rbp-4]
sal eax, 7
add eax, 77
```

```
int __outlined2(int x) {
  return x * 128 + 33;
}
```

```
mov eax, DWORD PTR [rbp-4]
sal eax, 7
add eax, 33
```



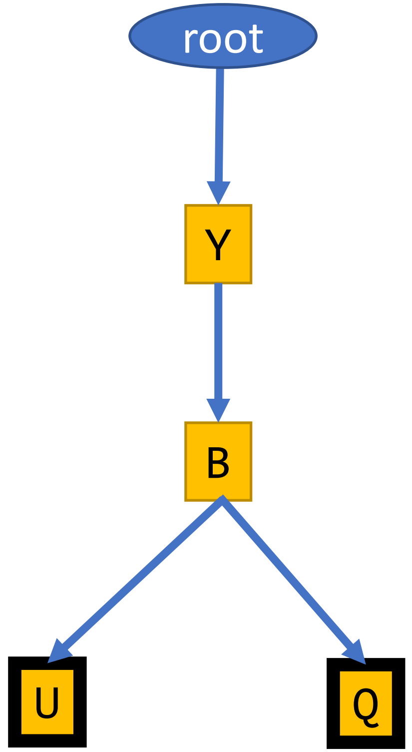
Global prefix tree: Hashing (in First Round CG)

a.c:

```
int __outlined1(int x) {
  return x * 128 + 77;
}
mov eax, DWORD PTR [rbp-4]   // Y
sal eax, 7                   // B
add eax, 77                  // U

int __outlined2(int x) {
  return x * 128 + 33;
}
mov eax, DWORD PTR [rbp-4]   // Y
sal eax, 7                   // B
add eax, 33                  // Q
```

Stable Hashes
(actual hashes are 64-bit)



Outlining More in Second Round CG

1) For an outlining candidate (whose sequence occurring at least 2 times)

- Check if the sequences occur in the **global prefix tree.**
- Adjust cost to 0 since it’s been already paid in other module.

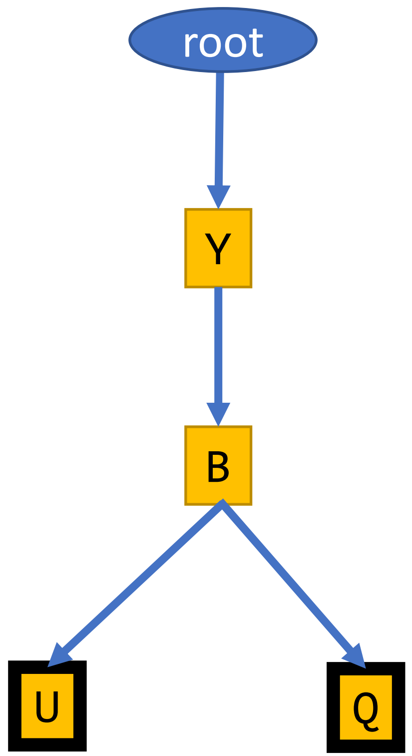
2) For sequence occurring only once in a module

- Iterate instruction sequences to see if there is a match in the **tree**.
- If so, optimistically outline such a singleton sequence. (see next slides)

Global prefix tree: Using for matching

b.c:

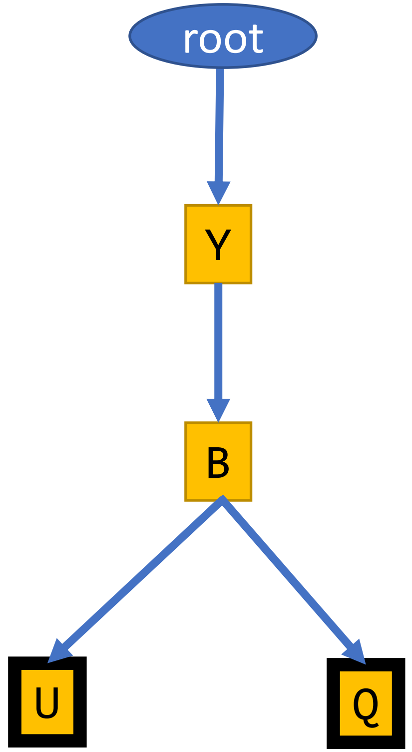
```
…
mov DWORD PTR [rbp-8], eax      // H
mov eax, DWORD PTR [rbp-4]      // Y
sal eax, 7                      // B
add eax, 77                     // U
add eax, 33                     // R
mov DWORD PTR [rbp-8], eax      // A
…
```



Global prefix tree: Using for matching

b.c:

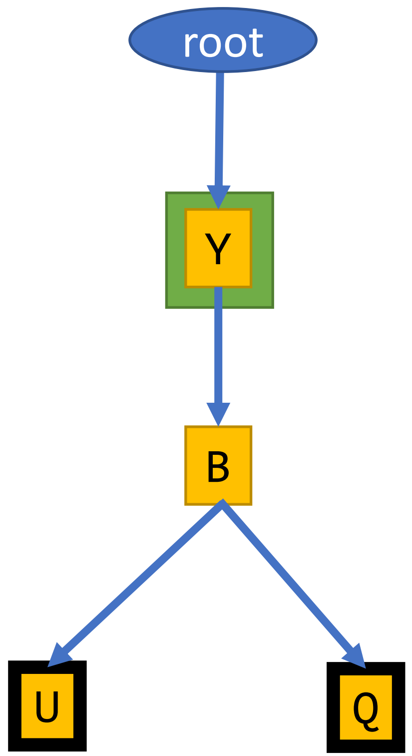
```
…
mov DWORD PTR [rbp-8], eax      // H
mov eax, DWORD PTR [rbp-4]      // Y
sal eax, 7                      // B
add eax, 77                     // U
add eax, 33                     // R
mov DWORD PTR [rbp-8], eax      // A
…
```



Global prefix tree: Using for matching

b.c:

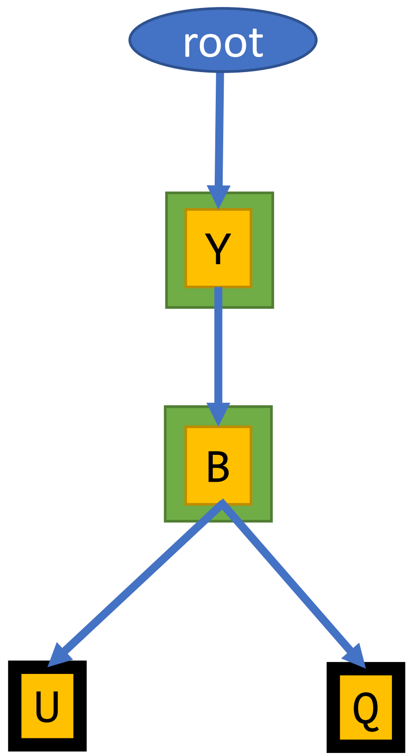
```
…
mov DWORD PTR [rbp-8], eax        // H
mov eax, DWORD PTR [rbp-4]        // Y
sal eax, 7                        // B
add eax, 77                       // U
add eax, 33                       // R
mov DWORD PTR [rbp-8], eax        // A
…
```



Global prefix tree: Using for matching

b.c:

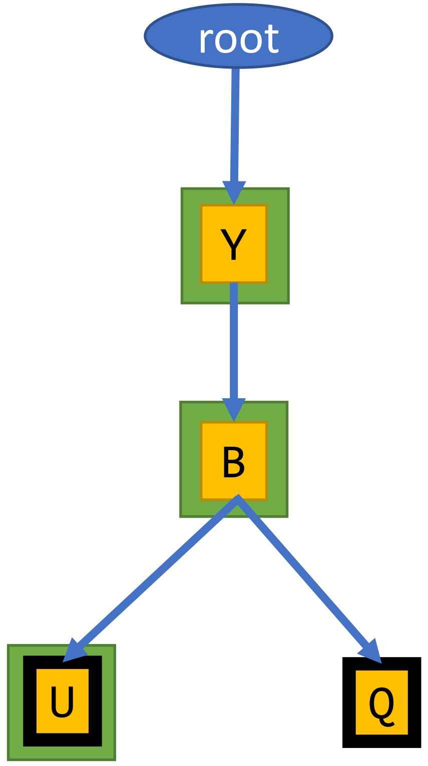
```
…
mov DWORD PTR [rbp-8], eax      // H
mov eax, DWORD PTR [rbp-4]      // Y
sal eax, 7                      // B
add eax, 77                     // U
add eax, 33                     // R
mov DWORD PTR [rbp-8], eax      // A
…
```



Global prefix tree: Using for matching

<u>b.c:</u>

```
…
mov DWORD PTR [rbp-8], eax      // H
mov eax, DWORD PTR [rbp-4]      // Y
sal eax, 7                      // B
add eax, 77                     // U
add eax, 33                     // R
mov DWORD PTR [rbp-8], eax      // A
…
```

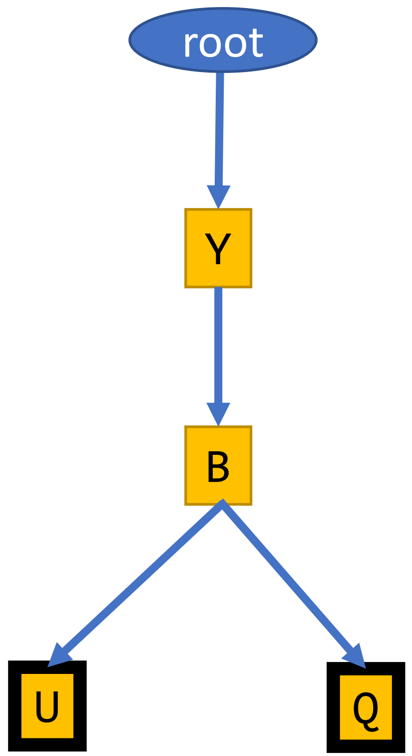


We found a match…
Outline this sequence!

Global prefix tree: Using for matching

<u>b.c:</u>

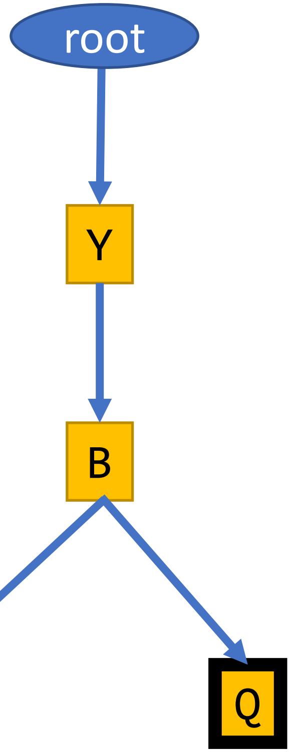
```
…
mov DWORD PTR [rbp-8], eax      // H
mov eax, DWORD PTR [rbp-4]      // Y
sal eax, 7                      // B
add eax, 77                     // U
add eax, 33                     // R
mov DWORD PTR [rbp-8], eax      // A
…
```



Global prefix tree: Using for matching

<u>b.c:</u>

```
…
mov DWORD PTR [rbp-8], eax      // H
mov eax, DWORD PTR [rbp-4]      // Y
sal eax, 7                      // B
add eax, 77                     // U
add eax, 33                     // R
mov DWORD PTR [rbp-8], eax      // A
…
```



Actually…

ThinLTO with 2-round CodeGen

a.c:

```
int f1(int x) {
  // ...more code...
  return x * 128 + 77;
}
int f2(int x) {
  // ...more code...
  return x * 128 + 77;
}
```

b.c:

```
int g(int x) {
  // ...more code...
  return x * 128 + 77;
}
```

```
int f1(int x) {
  // ...more code...
  return __outlined1(x);
}
int f2(int x) {
  // ...more code...
  return __outlined1(x);
}
```

```
int __outlined1(int x) {
  return x * 128 + 77;
}
```

```
int g(int x) {
  // ...more code...
  return __outlined2(x);
}
```

```
int __outlined2(int x) {
  return x * 128 + 77;
}
```

Outlined Function Deduplication

- Soundness in the presence of hash collision
  - Hashes only used to determine which outlined functions to create in module
  - Introduce unique names for outlined functions across modules by attaching
    - Module Id
    - Hash of machine instructions of outlined function
  - Enable link-once ODR to let the linker deduplicate functions
- Support for further outlining of outlined functions
  - Relevant when running machine outliner multiple times (in each CodeGen)
  - When hashing call, use hash of outlined functions only (not full unique name)
  - This enables more matching in global prefix tree!

Frame Code Optimizations

with examples for for AArch64/iOS

Homogeneous Frame Code for Size

- Prologue
  - Start with FP/LR save
  - SP pre-decrement by 16 byte in order while saving CSR
  - Explicit FP(X29) setting
  - Local allocation
- Epilogue
  - Local deallocation
  - SP post-increment by 16 byte in order while restoring CSR
  - End with FP/LR restore

```
(Prologue)
stp x29, x30, [sp, #-16]!
stp x20, x19, [sp, #-16]!
stp x22, x21, [sp, #-16]!
add x29, sp, #32
...

(Epilogue)
ldp x22, x21, [sp], #16
ldp x20, x19, [sp], #16
ldp x29, x30, [sp], #16
ret
```

Custom-Outlined Frame Code Helpers

- Synthesized helpers by compiler
  - Eagerly populate possible helpers in each module pass
  - Unique naming with LinkOnce-ODR to deduplicate helpers by linker
- Unwind code is still in place at each prologue site.

(Prologue)

```
stp x29, x30, [sp, #-16]!
bl _PROLOG_INTEGER_19202122
add x29, sp, #32
...
```

(Epilogue)

```
bl _EPILOG_INTEGER_21221920
ldp x29, x30, [sp], #16
ret
```

Optimizing Epilogue – Outlining FP/LR Restore

- Touching LR is tricky in outliner
- Use a scratch register, X16 to stash/restore LR value to the context of epilogue.
- Useful for a tail-call epilogue that a direct branch follows.

```
(Epilogue)
bl _EPILOG_INTEGER_21221920LRFP
ret

(Helpers)
_EPILOG_INTEGER_21221920LRFP:
mov x16, x30                  // Save LR of epilogue to X16
ldp x22, x21, [sp], #16
ldp x20, x19, [sp], #16
ldp x29, x30, [sp], #16       // Restore LR (of caller)
br x16                        // Jump on X16 back to epilogue
```

Optimizing Epilogue - Tail-Call Helper

- Function *return* is folded into the helper
- Branch (B) instead of Call (BL) at epilogue
- Return to the original caller from the helper
- Ideally, helpers can be merged at different offsets for further saving

(Epilogue)

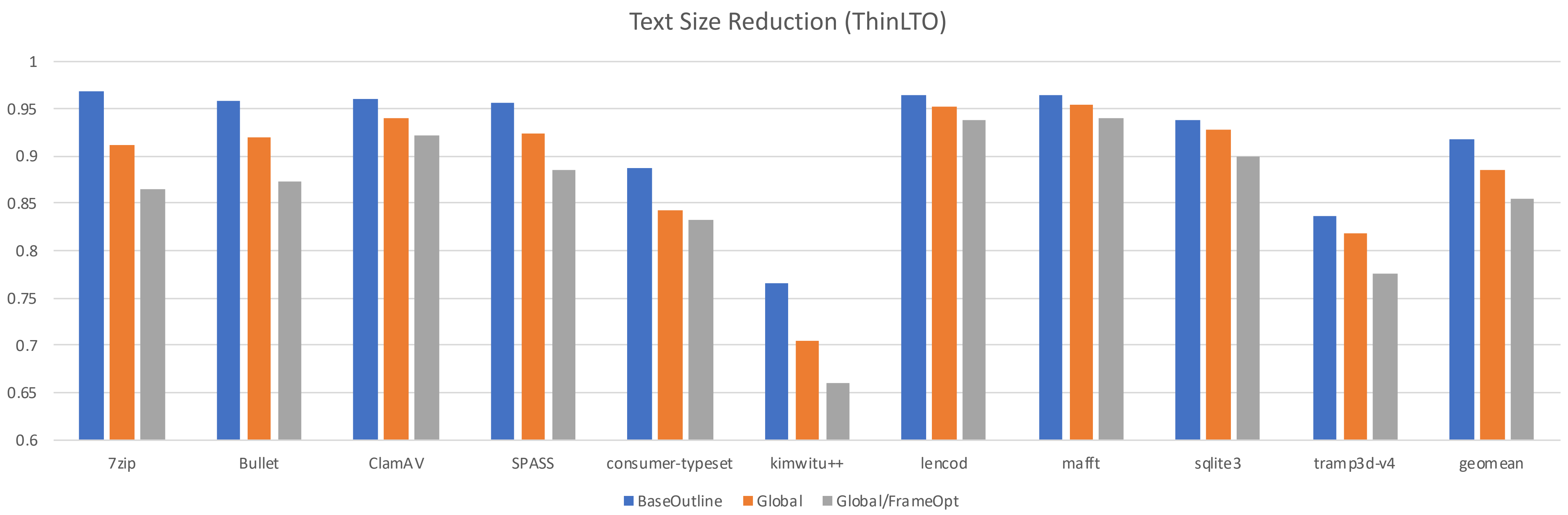
```
b _EPILOG_INTEGER_21221920LRFP_TAIL
```

(Helper)

```
_EPILOG_INTEGER_21221920LRFP_TAIL:
ldp x22, x21, [sp], #16
ldp x20, x19, [sp], #16
ldp x29, x30, [sp], #16
ret
```

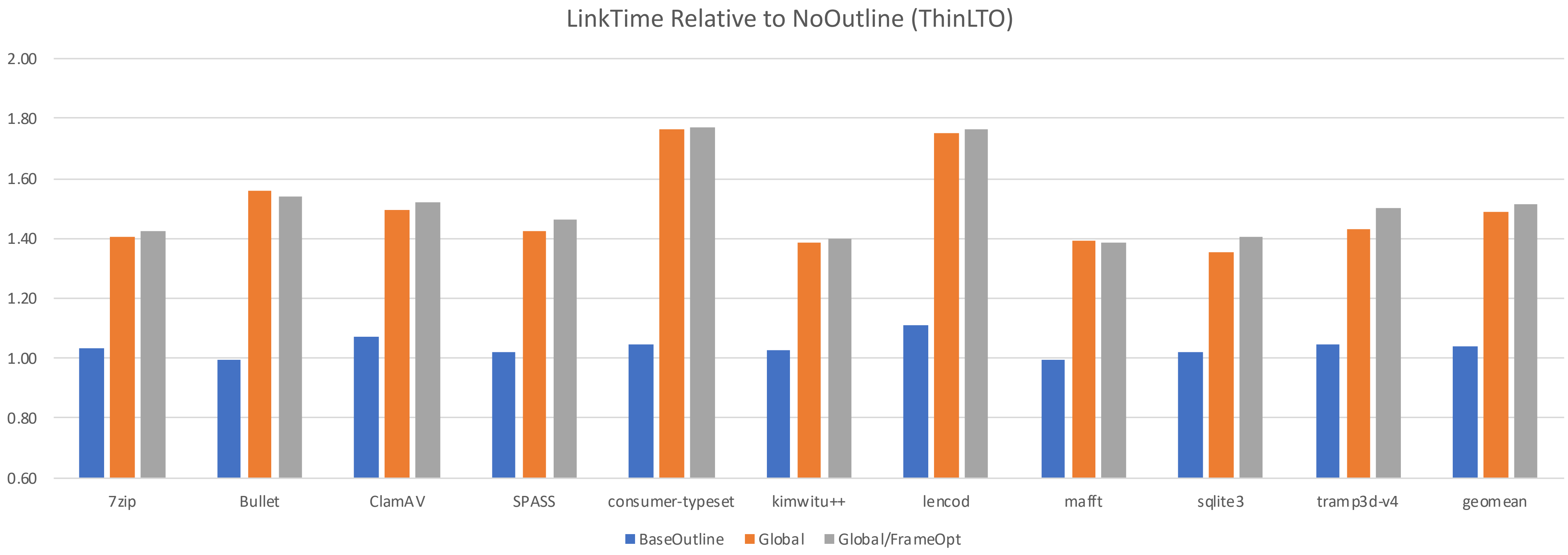
Evaluation

Global/FrameOpt Outliners with ThinLTO



- Global outliner saves 11%, which is already on par with LTO
- Global outliner + FrameOpt saves up to 15% on average.

LinkTime (ThinLTO + Linking)



- Link time slowdown is 1.5X on average.
- Caused by the repeated code gen and more deduplications
- Still, a fraction of LTO build time.

Evaluation with Some Large Applications

- Number of outlined instruction sequences almost doubles for large internal benchmark
- Total build time (compilation + link) is within ~5% overall wall-time overhead for large internal benchmark
- Even measured performance improved due to page faults reductions.

Future work

- Alternatives to running CodeGen twice
  - Persist hashes, re-use in later builds
  - Trading effectiveness for improved build times
- Build global suffix tree
  - Capture still missed opportunities that are not beneficial in any single module
- Make MIR fully (de)serializable
  - Save the time running the first part of codegen twice
- Avoid generating identical outlined functions
  - That then need to get folded by linker