The Present and Future of Interprocedural Optimization in LLVM

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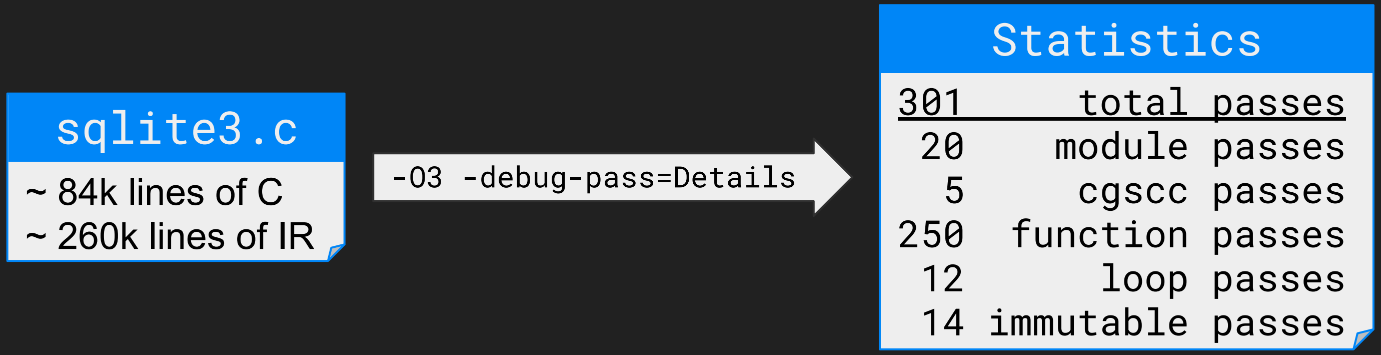
The Present

Kinds of IPO passes

- Inliner
  - AlwaysInliner, Inliner, InlineAdvisor, ...
- Propagation between caller and callee
  - Attributor[1], IP-SCCP, InferFunctionAttrs, ArgumentPromotion, DeadArgumentElimination, ...
- Linkage and Globals
  - GlobalDCE, GlobalOpt, GlobalSplit, ConstantMerge, ...
- Others
  - MergeFunction, OpenMPOpt[2], HotColdSplitting[3], Devirtualization[4]...

Checkout the IPO tutorial[5] for details!

Current State of IPO in LLVM



sqlite3.c

~ 84k lines of C
~ 260k lines of IR

```
-O3 -debug-pass=Details
```

Statistics

301	total passes
20	module passes
5	cgscc passes
250	function passes
12	loop passes
14	immutable passes

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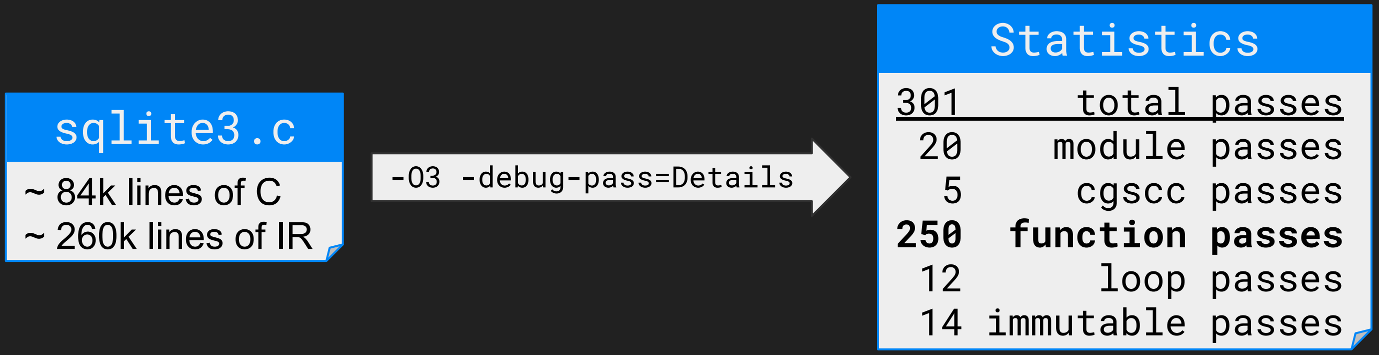

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>90% of passes are intraprocedural

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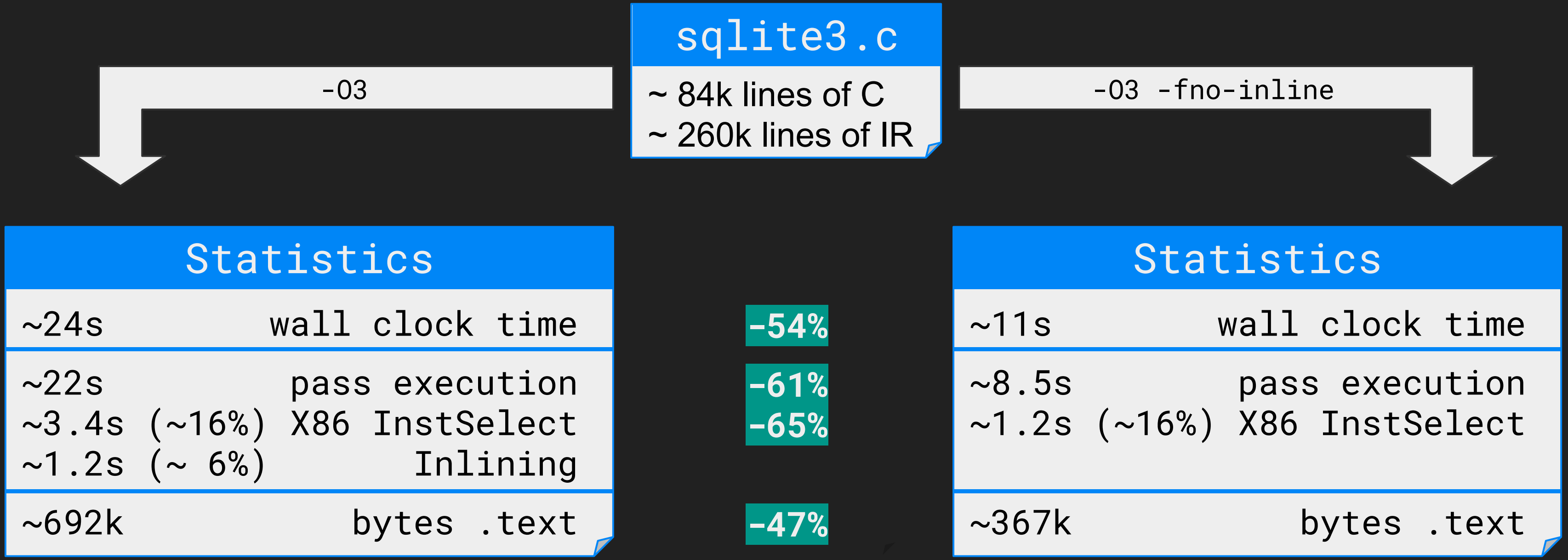

sqlite3.c

~ 84k lines of C
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-O3

-O3 -fno-inline

Statistics

~24s wall clock time

~22s pass execution
~3.4s (~16%) X86 InstSelect
~1.2s (~ 6%) Inlining

~692k bytes .text

-54%

-61%

-65%

-47%

Statistics

~11s wall clock time

~8.5s pass execution
~1.2s (~16%) X86 InstSelect

~367k bytes .text

>50% time & bytes spend as a *consequence* of inlining

Inlining - Benefits: Code specialization

```
static void foo(int x, bool c) {
  if (c) y = 1; else y = 2;
  use(x, y);

}

void caller1(int x) {
   foo(x, true);

}

void caller2(int x) {
   foo(x, false);

}
```

```
void caller1(int x) {
  use(x, 1);

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```

Inlining - Drawbacks: Code Duplication

```
static void foo(int x, bool c) {
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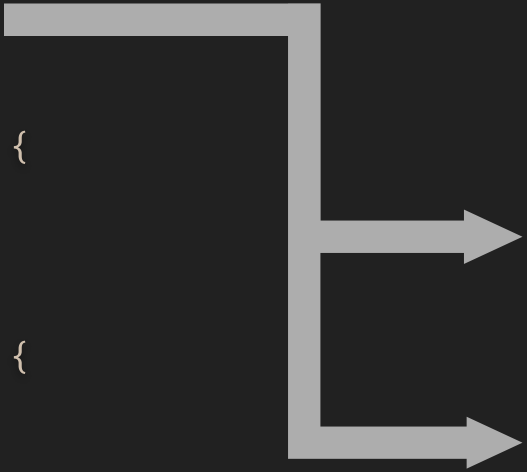

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}
```

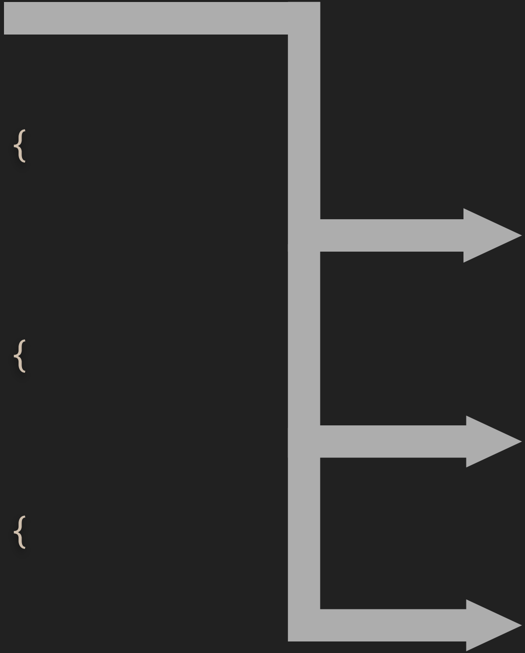

```
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  use(x, 1);
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  use(x, 2);
  /* more stuff */
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}
```
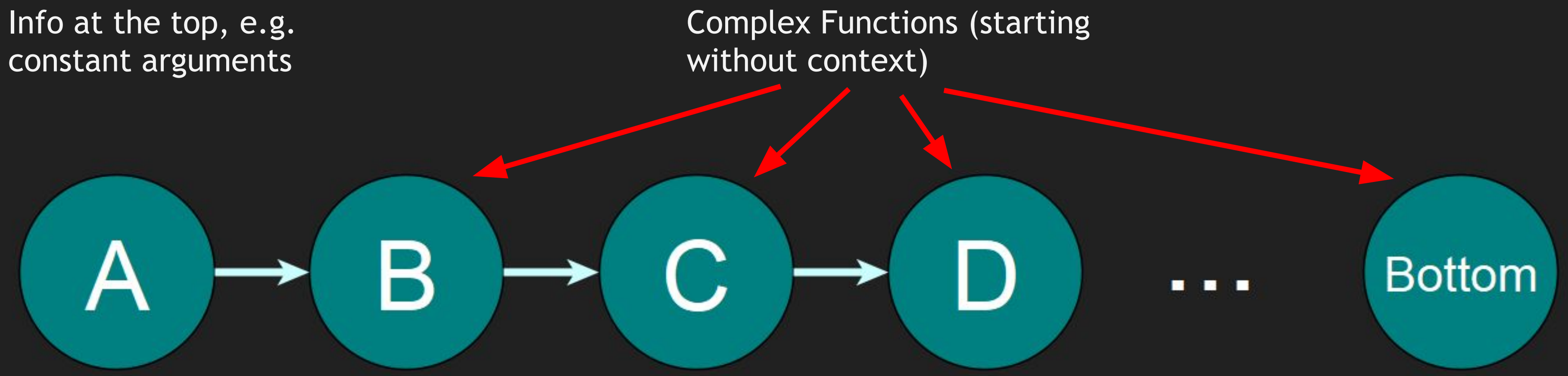

Inlining - Drawbacks: Inline Order



Info at the top, e.g. constant arguments

Complex Functions (starting without context)

Inlining - Drawbacks: Inline Order

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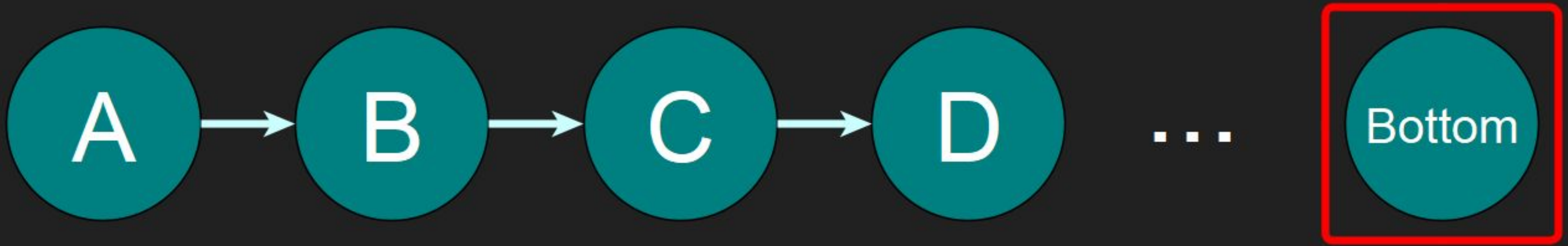
constant arguments



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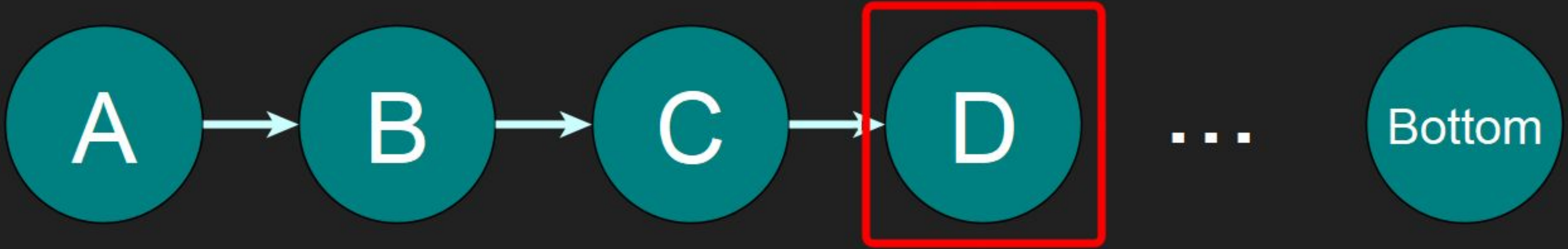
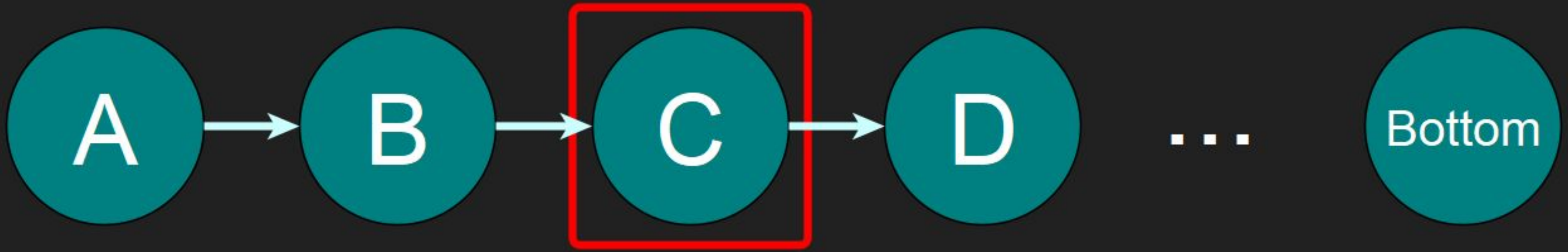


Inlining - Drawbacks: Inline Order

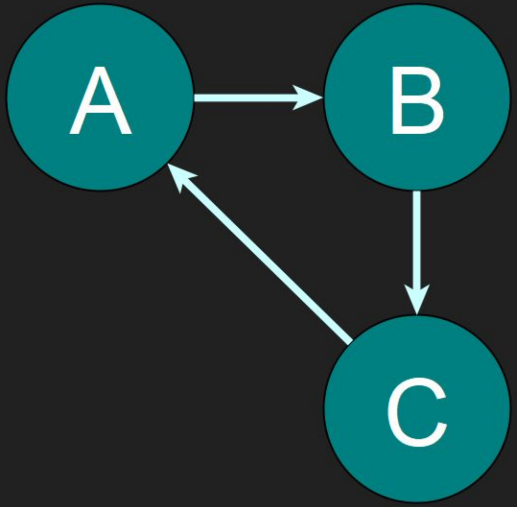
Info at the top, e.g.
constant arguments

Maybe the inliner
stops here

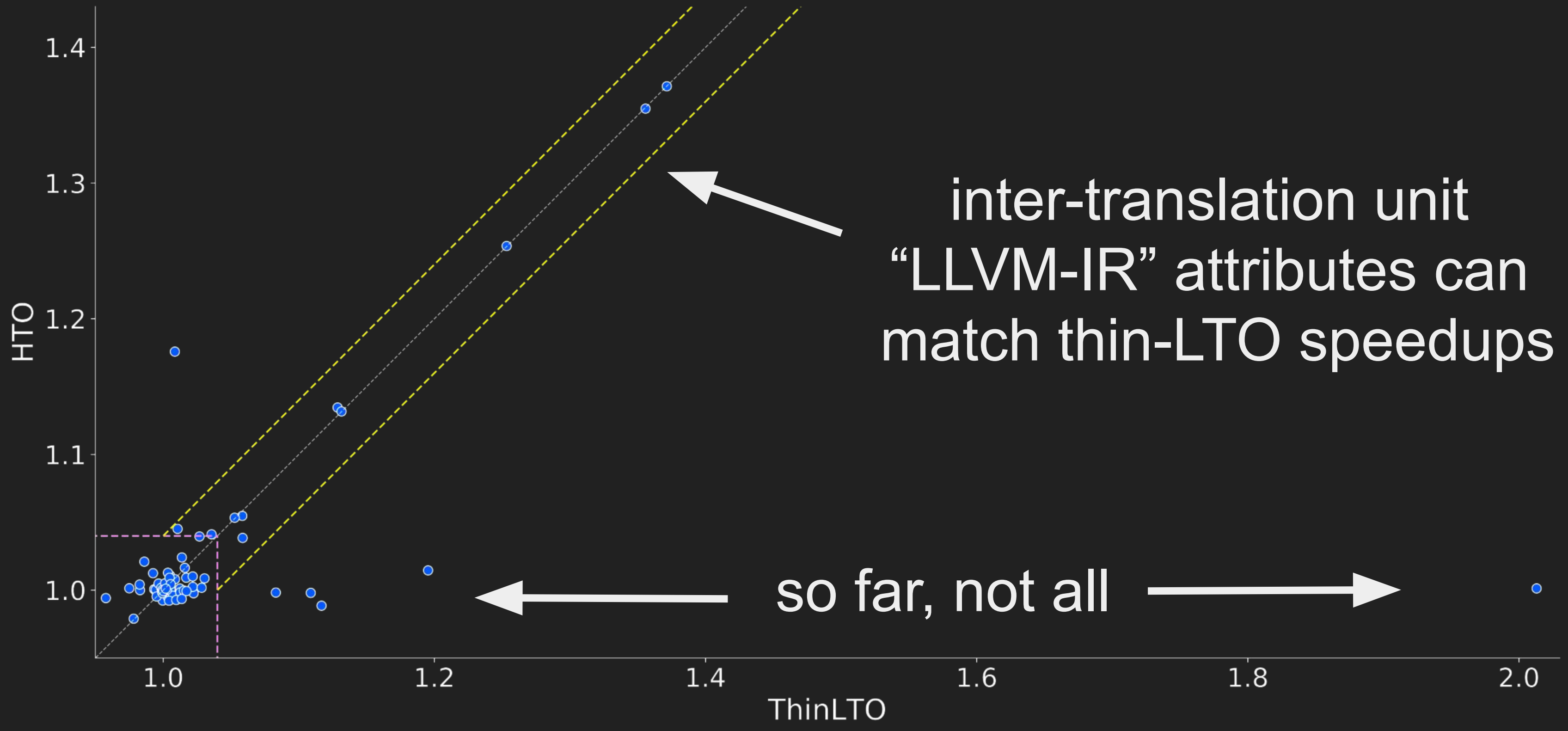


Inlining - Drawbacks: Inline Order

Strongly Connected Components (SCCs) have no top-down/bottom-up order



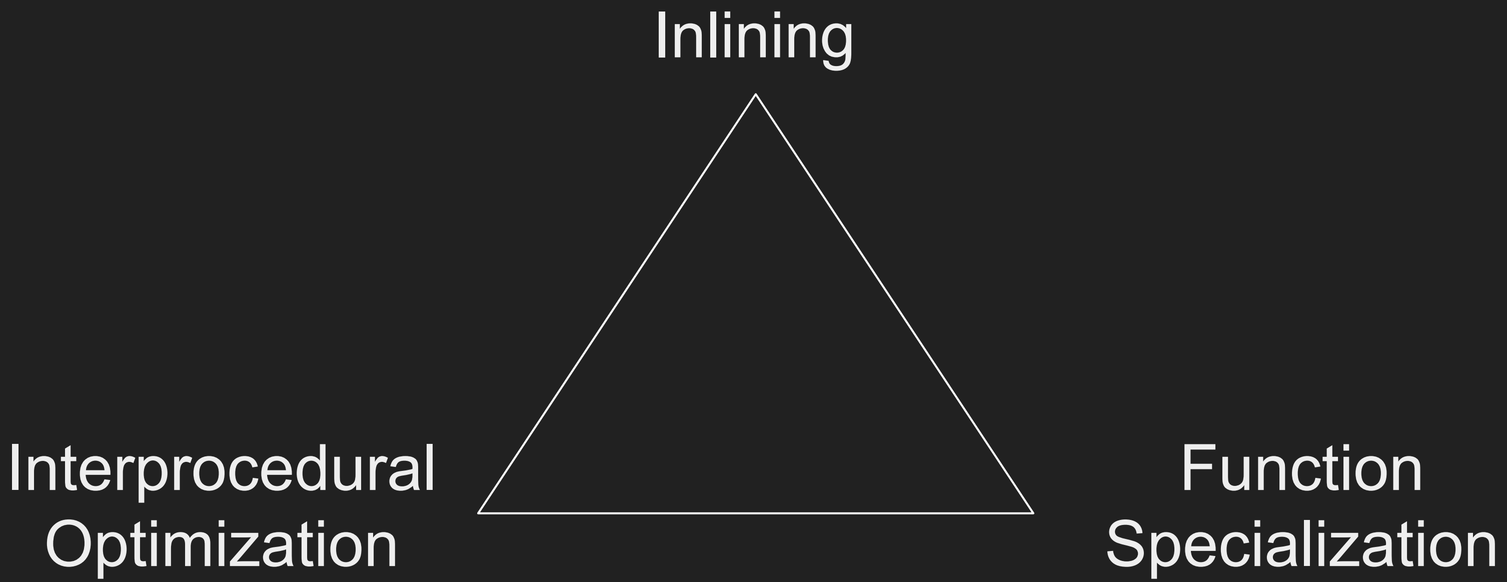
Inlining - Alternatives: thin-LTO[7] vs HTO[8]



inter-translation unit “LLVM-IR” attributes can match thin-LTO speedups

so far, not all

Design Space

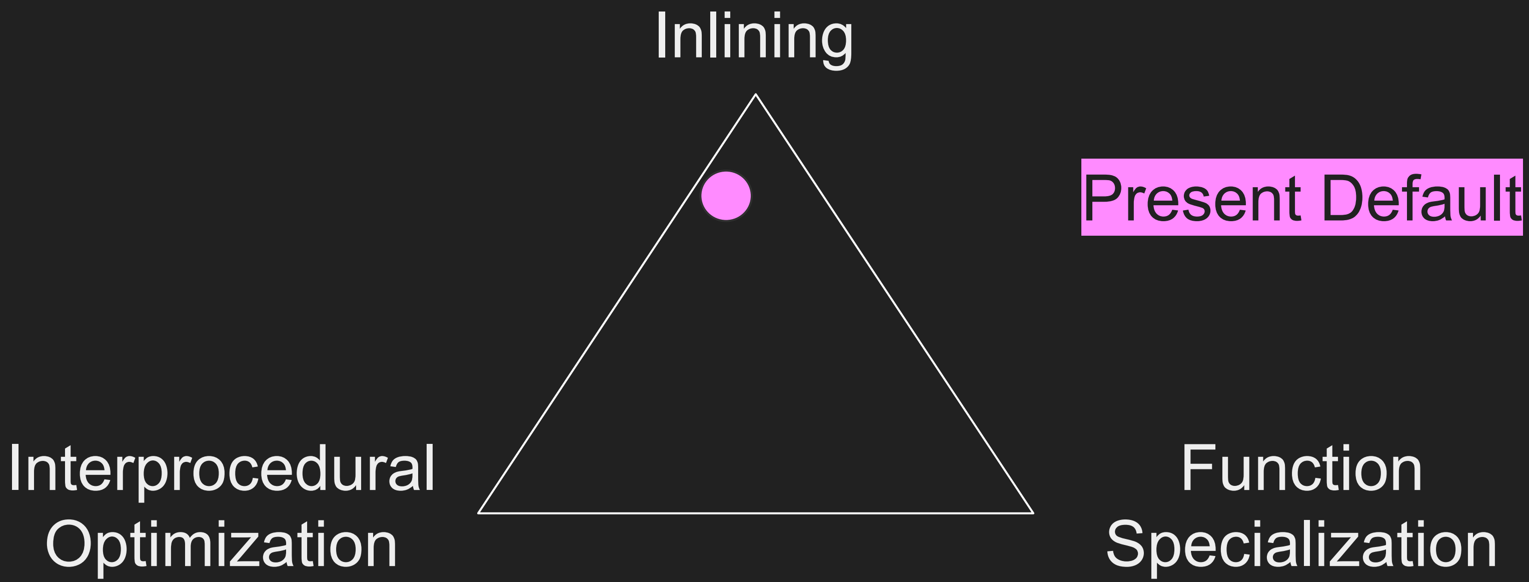


Inlining

Interprocedural Optimization

Function Specialization

Design Space



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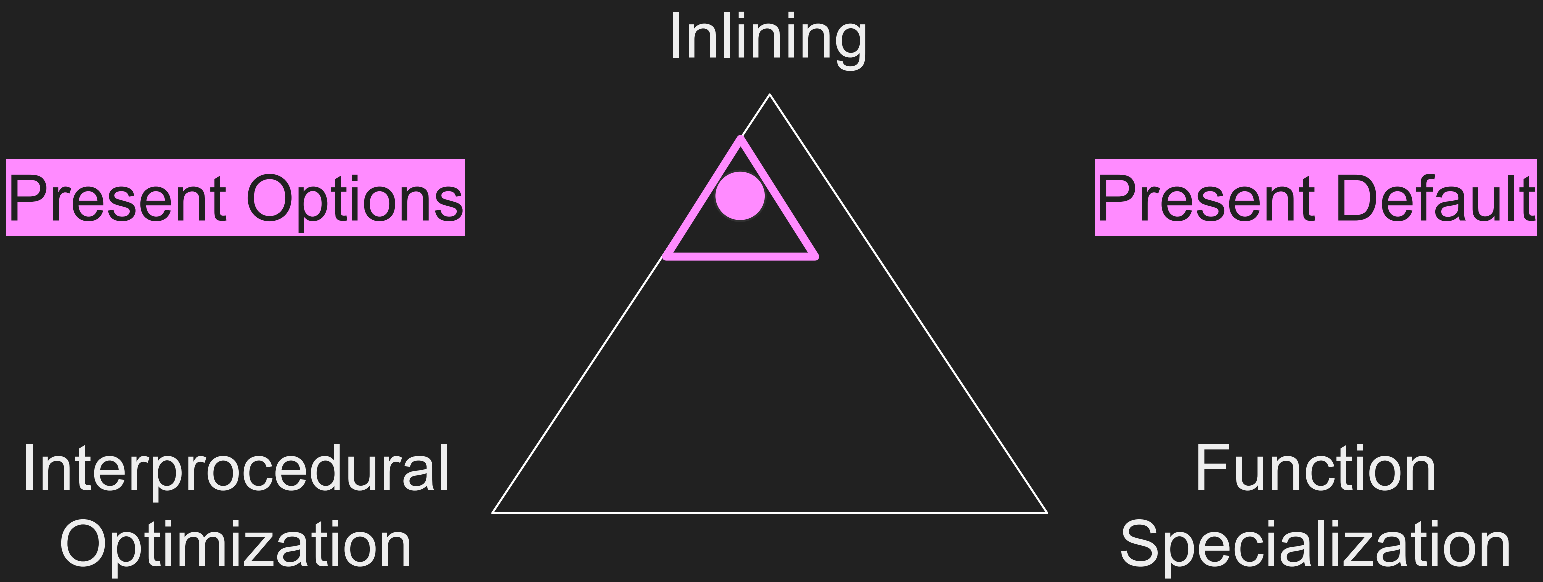

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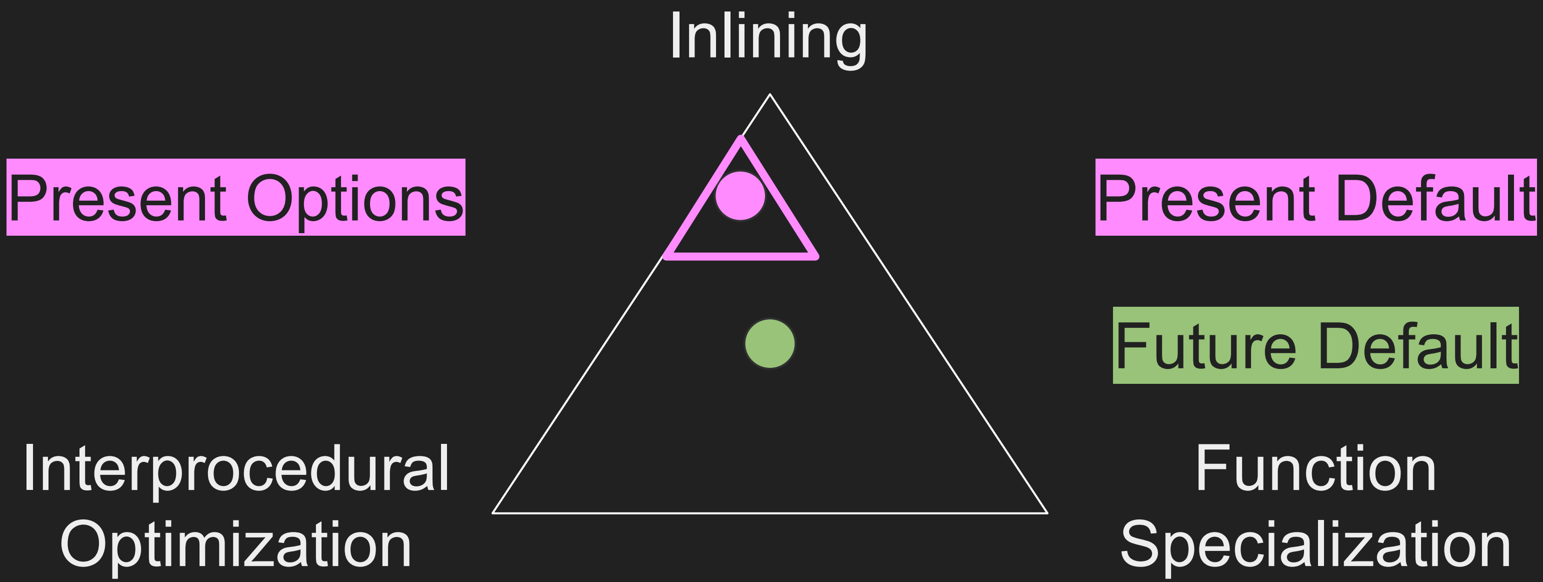


Inlining

Present Options

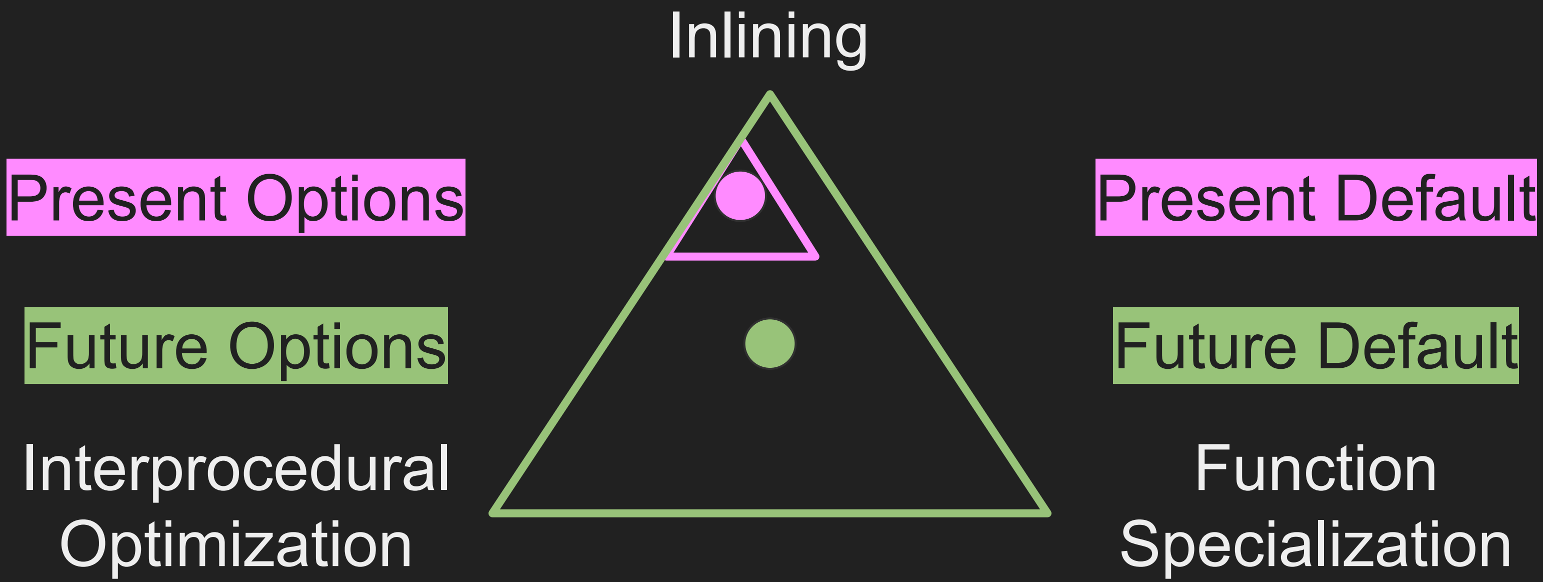
Present Default

Future Default

Interprocedural Optimization

Function Specialization

Design Space



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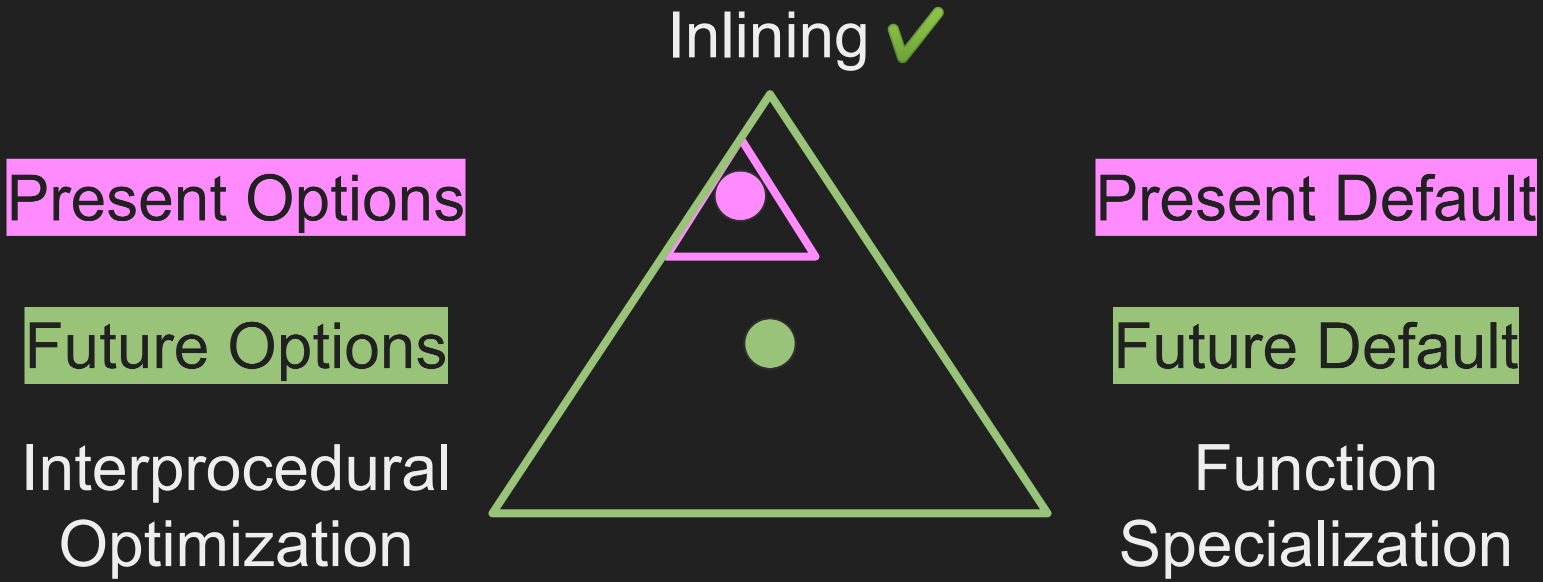

Inlining ✓

Present Options

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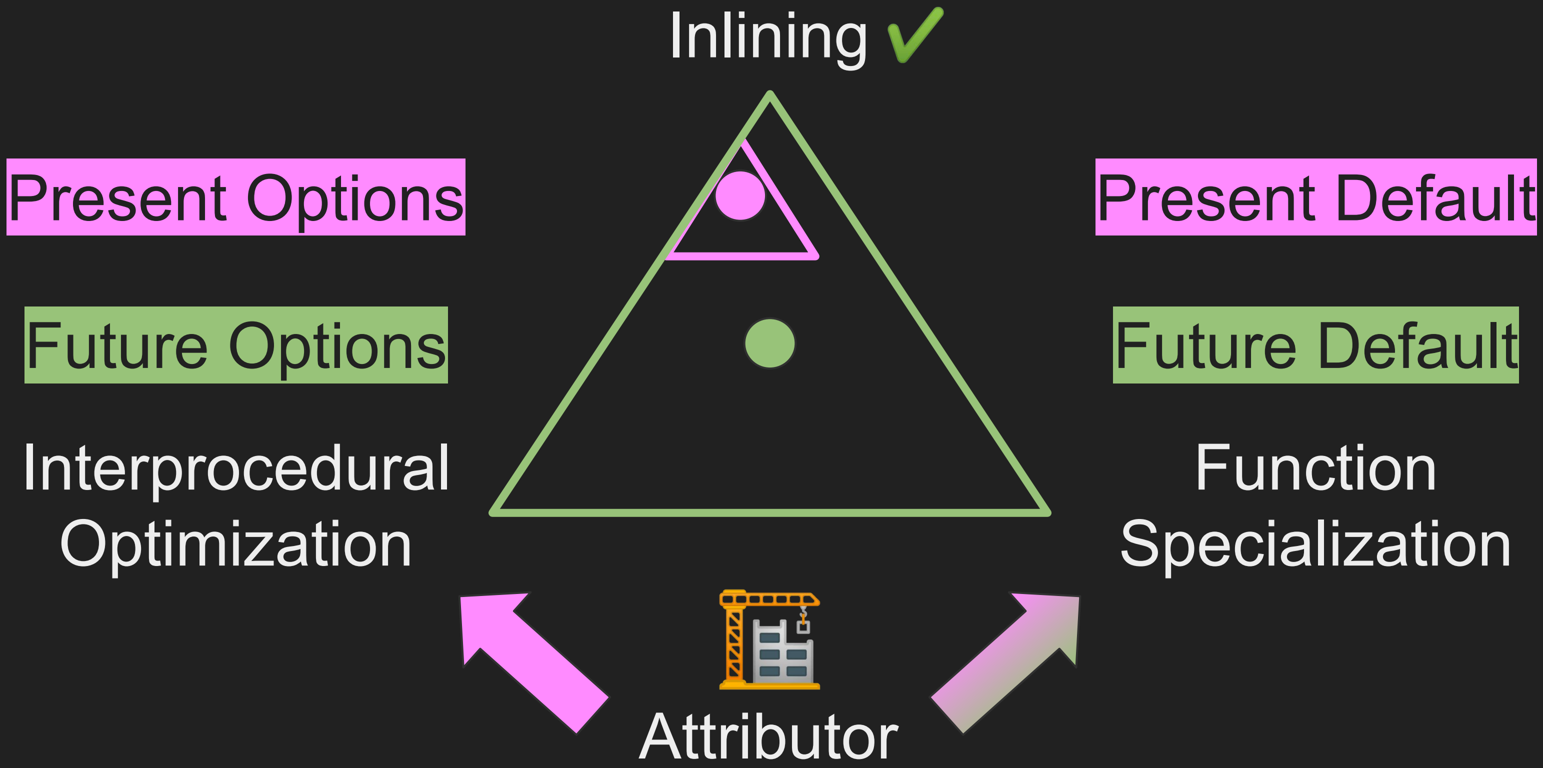
Future Options

Future Default

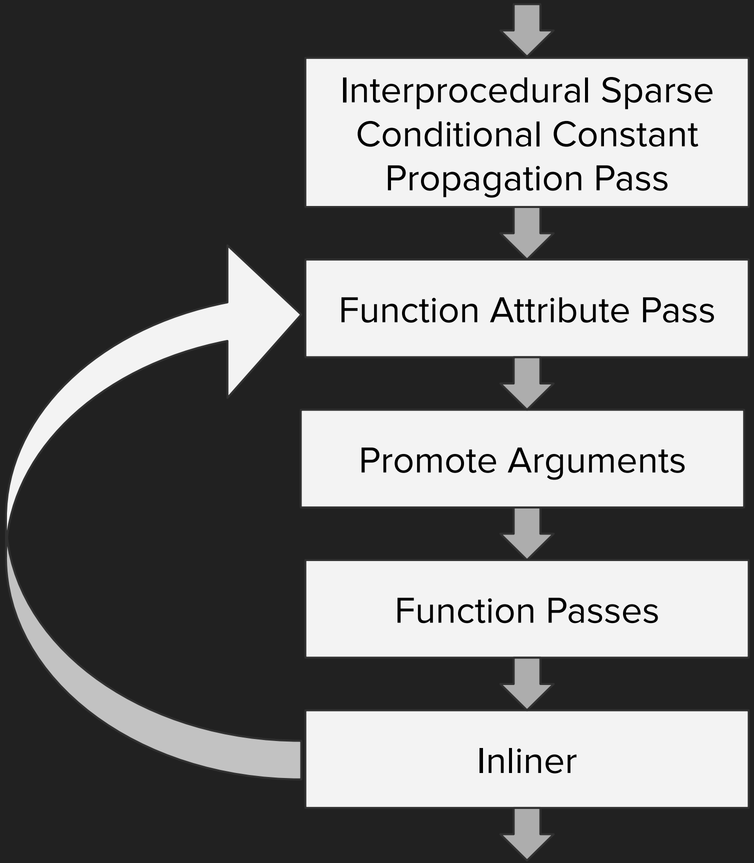
Interprocedural Optimization

Function Specialization

Design Space



Pass Ordering



Interprocedural Sparse Conditional Constant Propagation Pass

Function Attribute Pass

Promote Arguments

Function Passes

Inliner

```
void unknown(int &x);

static void check_n_rec(int n, int &x, int &y) {
  if (x) unknown(x);
  if (n) check_n_rec(n-1, y, x);
}

int test(int n) {
  int x = 0, y = 0;
  check_n_rec(n, x, y);
  return x + y;
}
```

The Future

Attributor

The Attributor[1,9] is an *interprocedural fixpoint iteration framework*; with lots of built-in features.

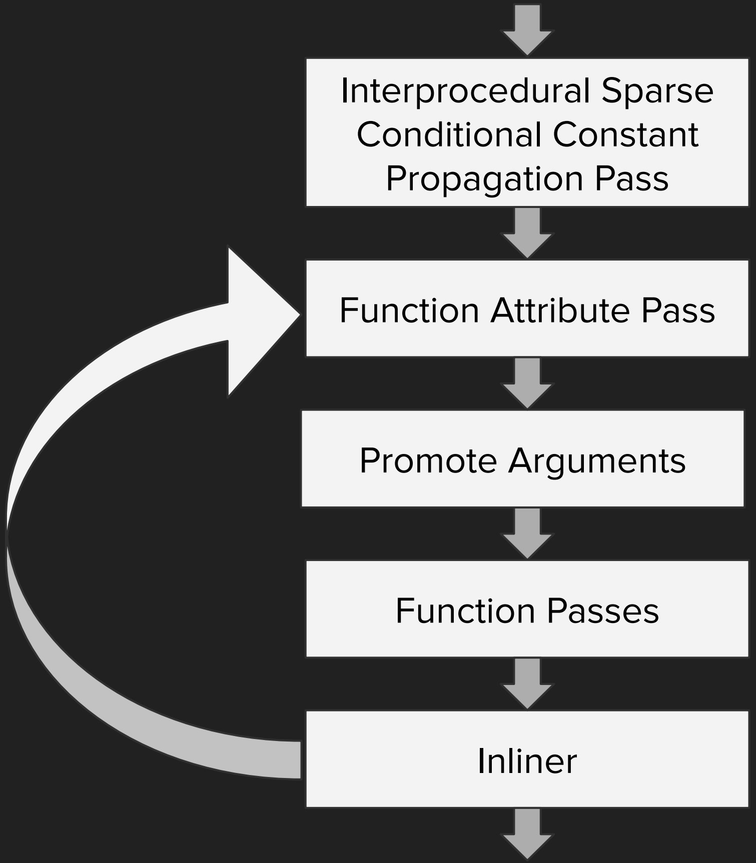
Attributor covers many IPO passes

- infers almost all LLVM-IR attributes
  ✓ (Reverse)Post Order Function Attribute Pass

- simplifies arguments, branches, return values and ...
  ✓ IP-SCCP*, Called Value Propagation

- rewrites function signatures
  ✓ Argument Promotion, Dead Argument Elimination

Pass Ordering



```
void unknown(int &x);

static void check_n_inc(int n, int &x, int &y) {
  if (x) unknown(x);
  if (n) check_n_inc(n-1, y, x);
}

int test(int n) {
  int x = 0, y = 0;
  check_n_inc(n, x, y);
  return x + y;
}
```

Dataflow Iterations

```
void unknown(int &x);
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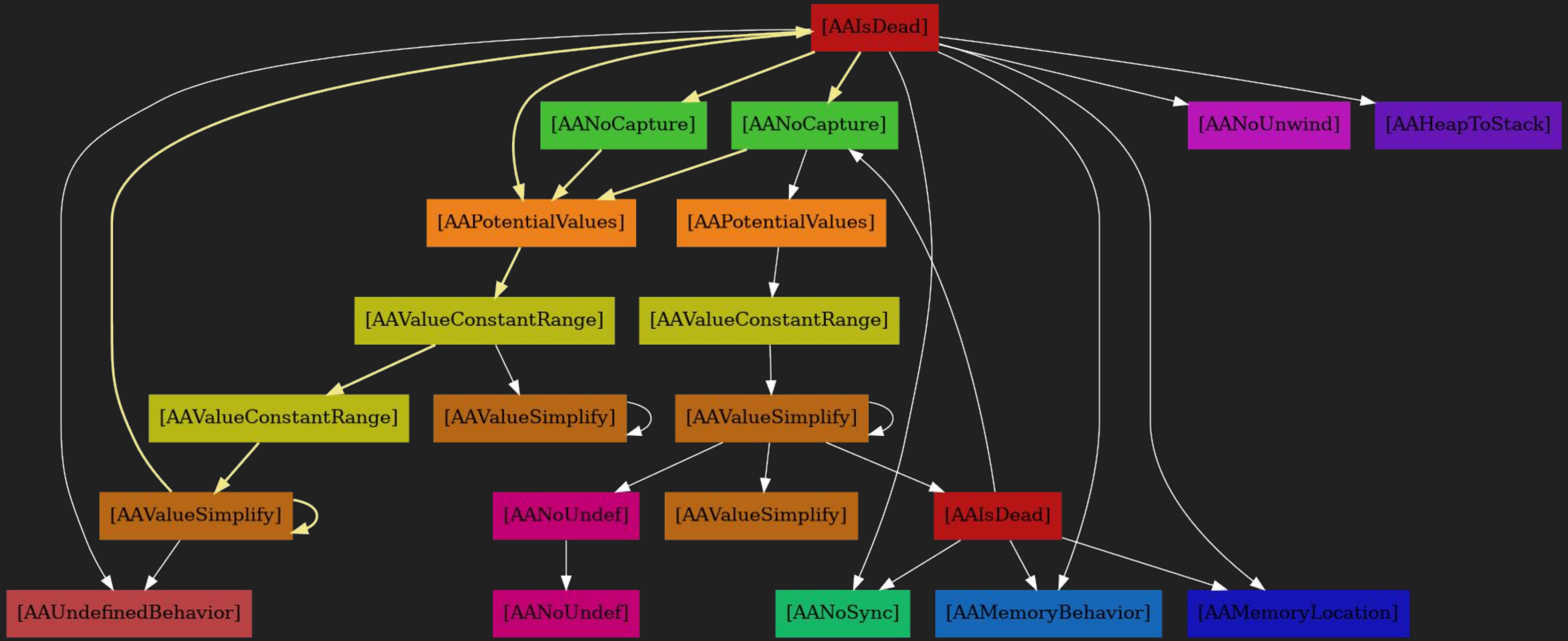

Function Specialization

```
__attribute__((linkonce_odr))
void foo(int x, bool c) {
  if (c) y = 1; else y = 2;
  use(x, y);
}



void caller1(int x) {
  foo(x, false);
}
void caller2(int x) {
  foo(x, false);
}
void caller3(int x) {
  foo(x, true);
}
```

```
__attribute__((linkonce_odr))
void foo(int x, bool c) {
  if (c) y = 1; else y = 2;
  use(x, y);
}
static void foo.internal(int x, bool c) {
  if (c) y = 1; else y = 2;
  use(x, y);
}

void caller1(int x) {
  foo.internal.false(x);
}
void caller2(int x) {
  foo.internal.false(x);
}
void caller3(int x) {
  foo.internal.true(x);
}
```

Function Specialization

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}
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  use(x, 2);
}
static void foo.internal.true(int x) {
  use(x, 1);
}
void caller1(int x) {
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```
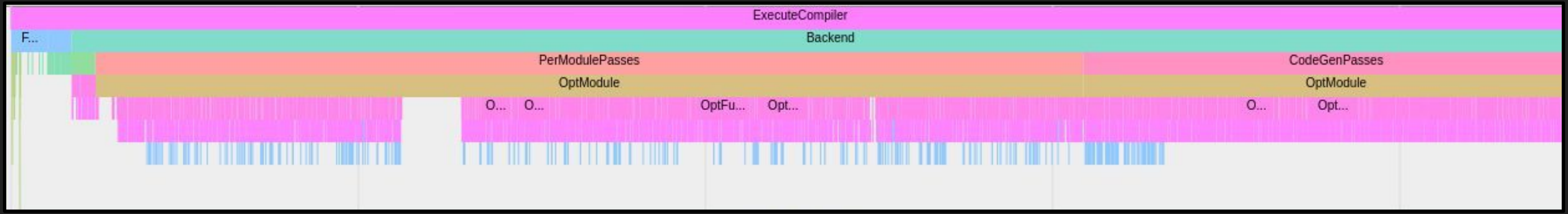
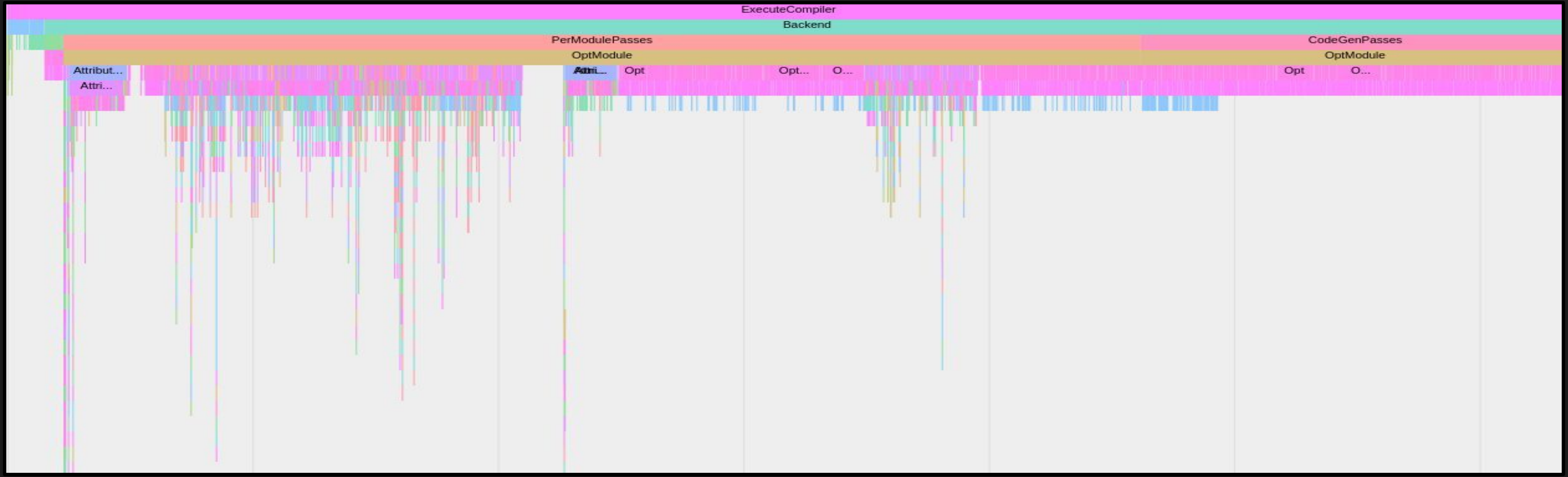

Time Traces


ExecuteCompiler
F...
Backend
PerModulePasses
CodeGenPasses
OptModule
OptModule
O...
O...
OptFu...
Opt...
O...
Opt...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How To Get There

Intrinsic & Library Functions

State

- *Most* intrinsics & library functions have *some* attributes

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- ~~*Most* intrinsics & library functions have *some* attributes~~
- *Most* intrinsics & library functions miss *a lot* of attributes

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- ~~*Most* intrinsics & library functions have *some* attributes~~
- *Most* intrinsics & library functions miss *a lot* of attributes

Solutions (in progress)

- Default attributes for intrinsics, you need to opt-out
- Revisit library functions and add attributes systematically

Intrinsic & Library Functions

llvm-test-suite/SingleSource/Benchmarks/BenchmarkGame/fannkuch.c

```
[Heap2Stack] Bad user:  call void @llvm.memcpy.p0i8.p0i8.i64(...) may-free  the allocation
[Heap2Stack] Bad user:  call void @llvm.memcpy.p0i8.p0i8.i64(...) may-free  the allocation
[Heap2Stack]: Removing calloc call:  %call = call noalias dereferenceable_or_null(44)
                                                 i8* @calloc(i64 noundef 11, i64 noundef 4)
```

3x heap to stack + follow up transformations:
~5% speedup

Introduce & Utilize New Attributes

Frontend:

- generic LLVM-IR attributes[8]
- “access” (like GCC[10])

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Introduce & Utilize New Attributes

Frontend:

- generic LLVM-IR attributes[8], i.a., `__attribute__((fn_arg("willreturn")))`
- "access" (like GCC[10]), i.a., `__attribute__ ((access (read_only, 1))) int puts (const char*)`

LLVM-IR:

- fine-grained memory effects:
  - `writes(@errno,...)`
  - `2^{inaccessible,argument,global,...}`
- `potential values`
  - `value(null, arg(0), @global, ...)`

Attributor - Testing

State

- *reasonable* unit test coverage
- *no* regular (=CI) builds

Solutions

- Try it out, report and track down bugs
- Setup buildbot(s) that enable the Attributor (anyone?)

Attributor - Memory Overhead

State

- *Way* better than in the last release
- Mostly an issue for the module-wide pass, not the call graph pass

Solutions (in progress)

- Drop Attributor state that is not useful anymore eagerly
- Minimize the number of Abstract Attributes created

Attributor - Compile Time Overhead

State

- *Improved* compared to the last release
- Issue for both the module-wide pass and the call graph pass

Solutions (in progress)

- Improve the schedule order (less updates, better locality, ...)
- Avoid costly deductions or perform them conditionally
- Minimize the number of Abstract Attributes created

Attributor - Selective Investment

Focus on hot code; look at otherwise cold code only as a consequence

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```c
static void foo() { ... }
static int* bar() { ...; return ...; }
static void baz(int *) { ... }

extern void __attribute__((cold)) sink();
void hotcold(int cond) {
  int *p = ...;
  if (cond) {
    p = bar();
    sink();
    foo();
  }
  baz(p);
}
```

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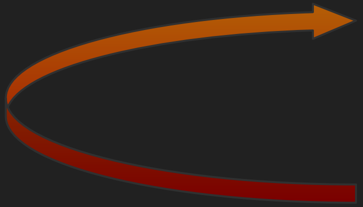

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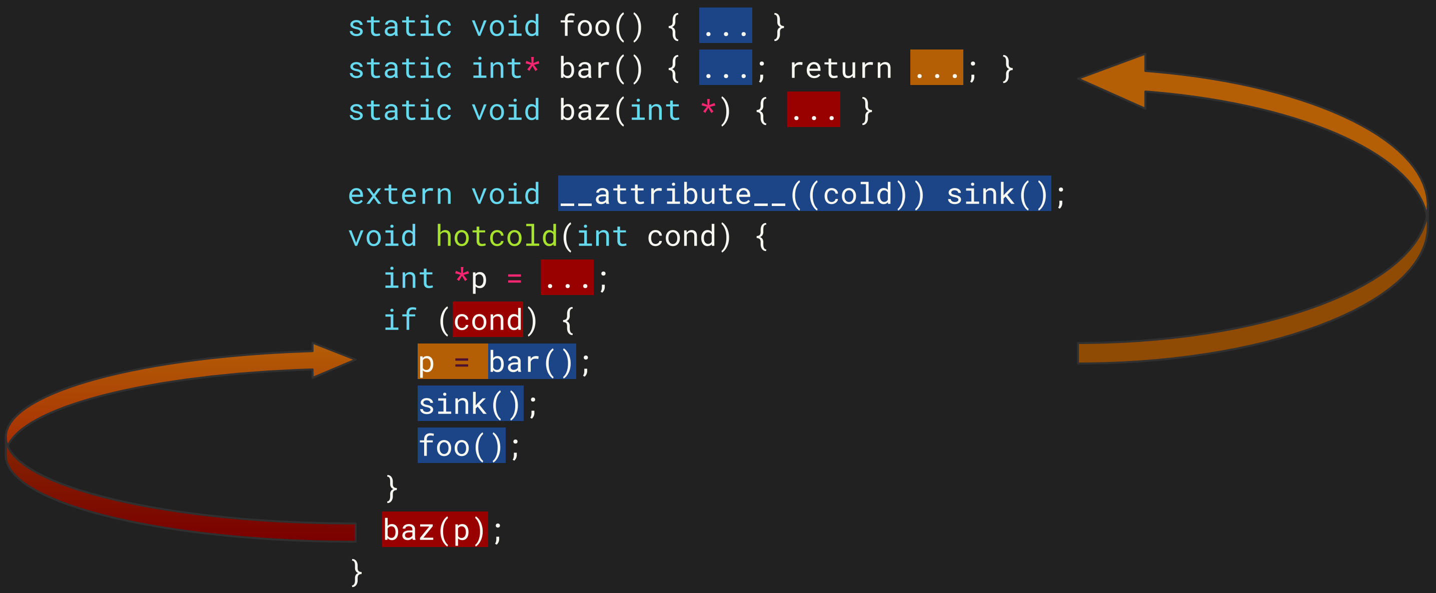

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    foo();
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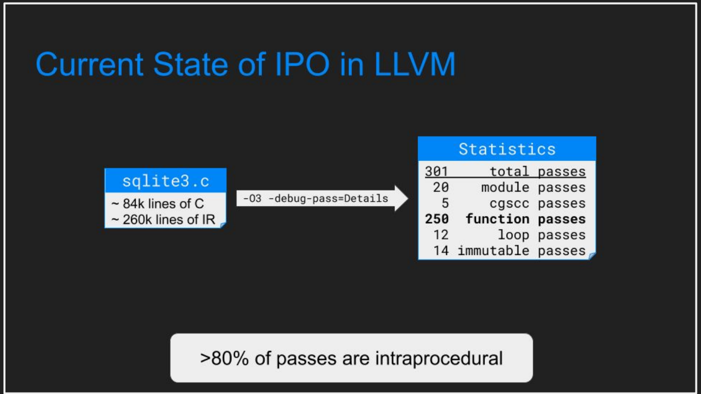
```

Conclusions



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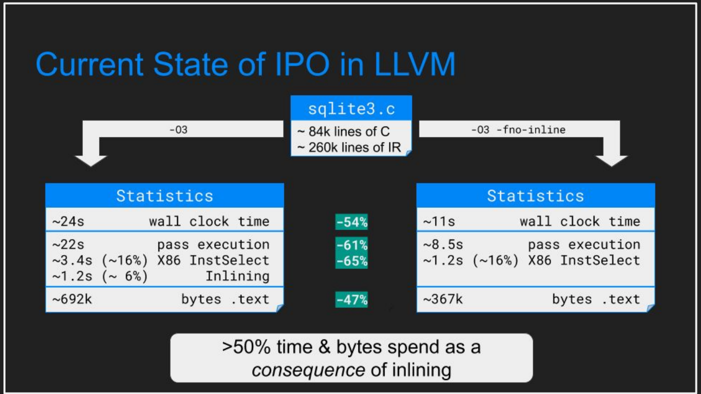

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Statistics
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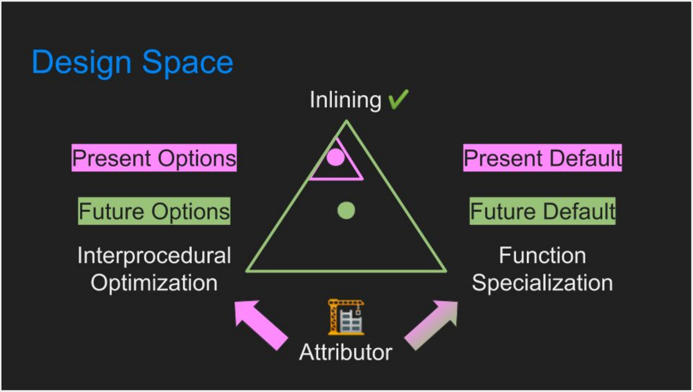
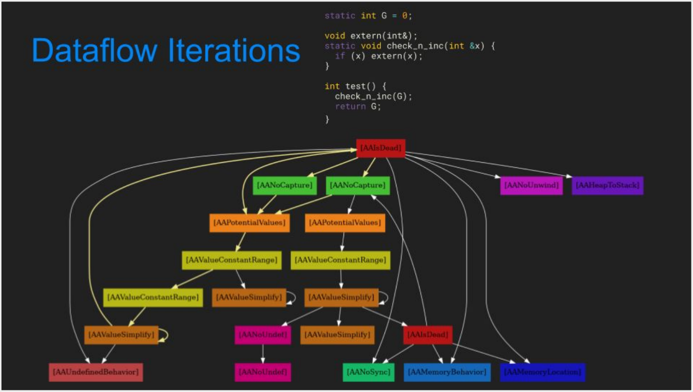
>50% time & bytes spend as a *consequence* of inlining



Design Space



Dataflow Iterations

```
static int G = 0;

void extern(int&);
static void check_n_inc(int &x) {
  if (x) extern(x);
}

int test() {
  check_n_inc(G);
  return G;
}
```

References

1. Tech talk: The Attributor: A Versatile Inter-procedural Fixpoint, J. Doerfert, S. Stipanovic, H. Ueno, LLVM Developers' Meeting 2019
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