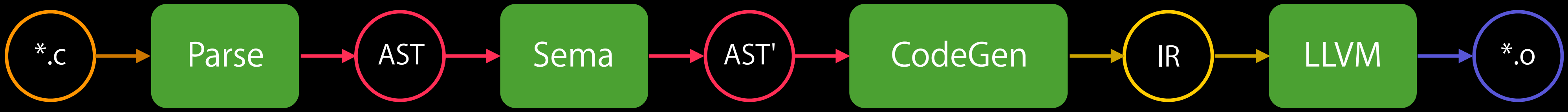
Swift Intermediate Language

A high level IR to complement LLVM

Joe Groff and Chris Lattner

Why SIL?

Clang


*.c

Parse

AST

Sema

AST'

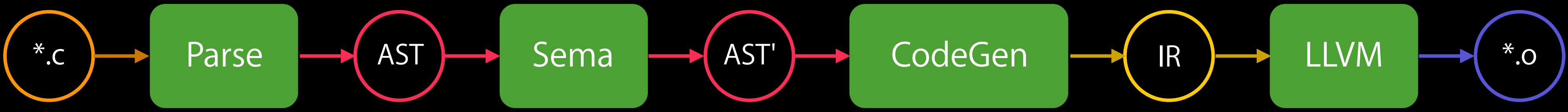
CodeGen

IR

LLVM

*.o

Clang



*.c → Parse → AST → Sema → AST' → CodeGen → IR → LLVM → *.o

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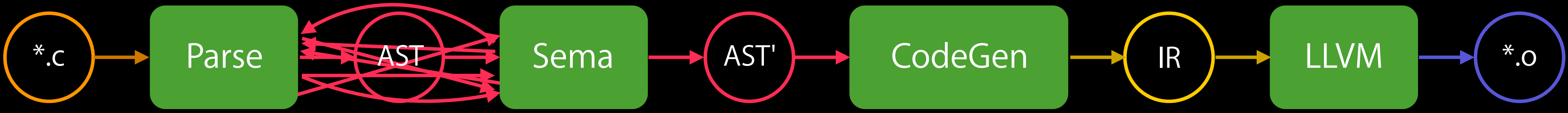

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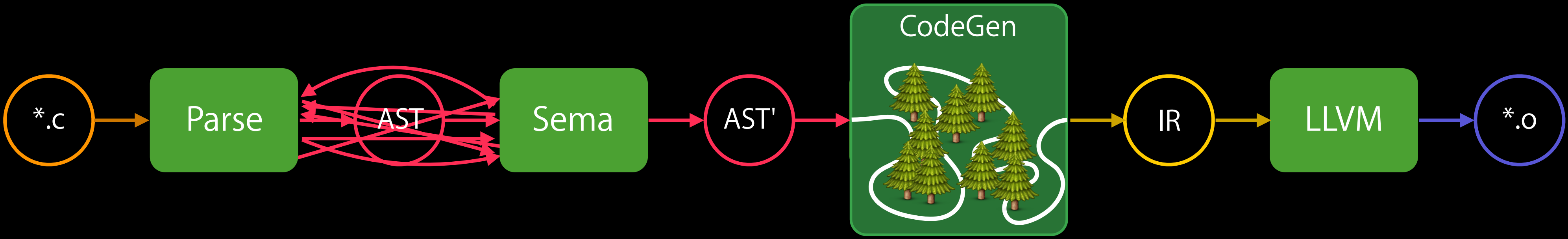

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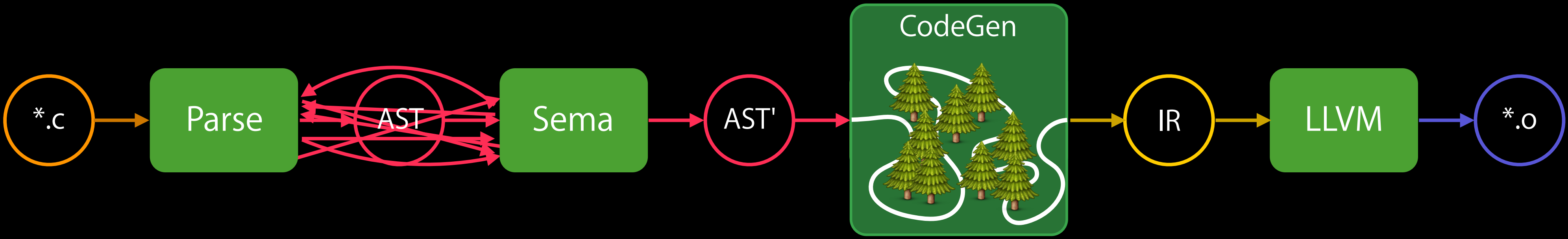

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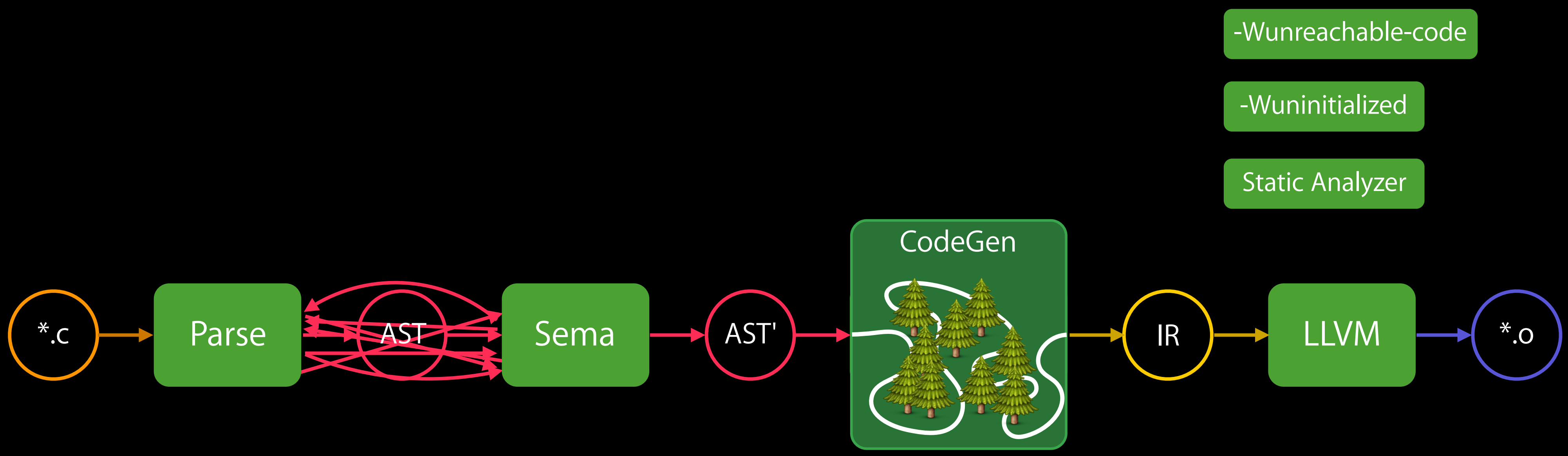

-Wunreachable-code

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Static Analyzer

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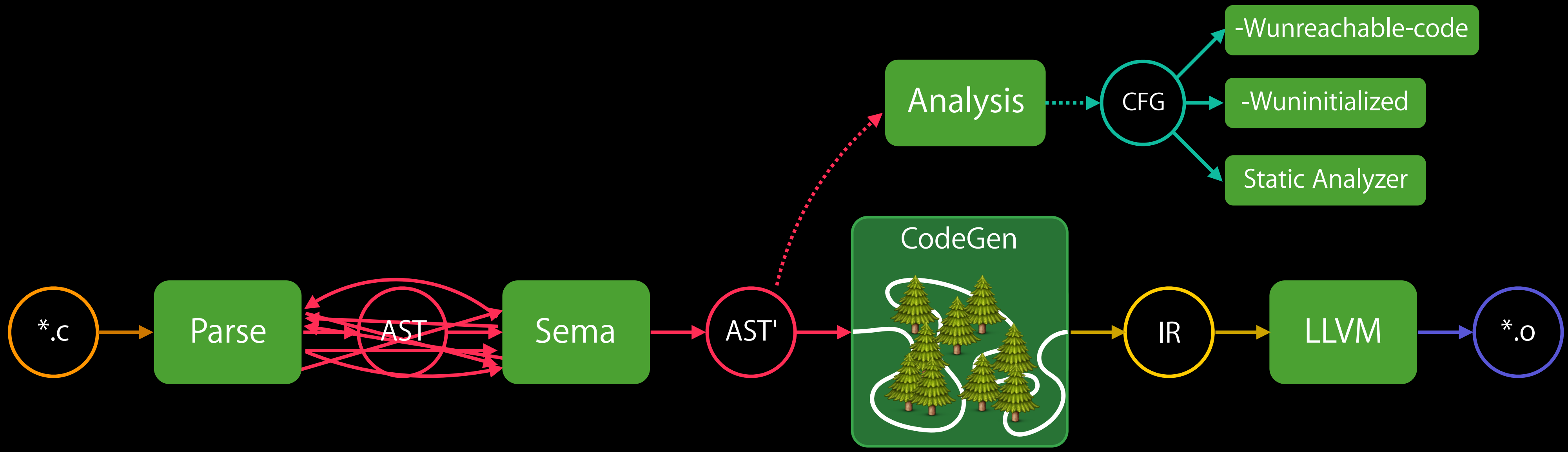
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Analysis
CFG
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Clang

Wide abstraction gap between source and LLVM IR

IR isn't suitable for source-level analysis

CFG lacks fidelity

CFG is off the hot path

Duplicated effort in CFG and IR lowering

Swift

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Higher-level language

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- Move more of the language into code

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Safe language

- Uninitialized vars, unreachable code should be compiler errors
- Bounds and overflow checks

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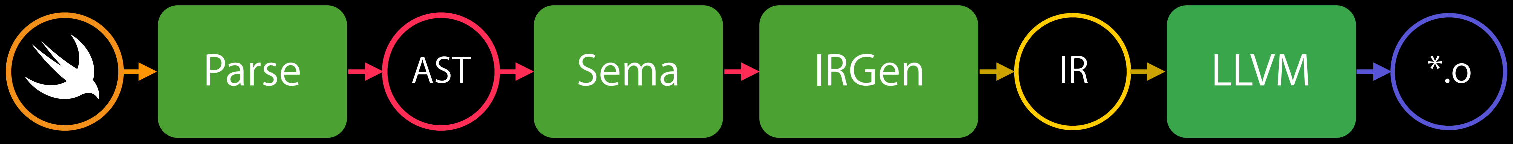

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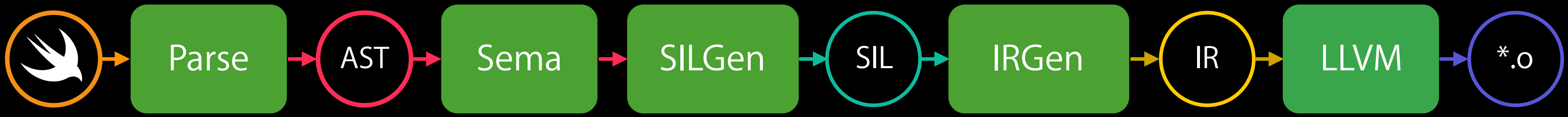

Parse → AST → Sema → SILGen → SIL → IRGen → IR → LLVM → *.o

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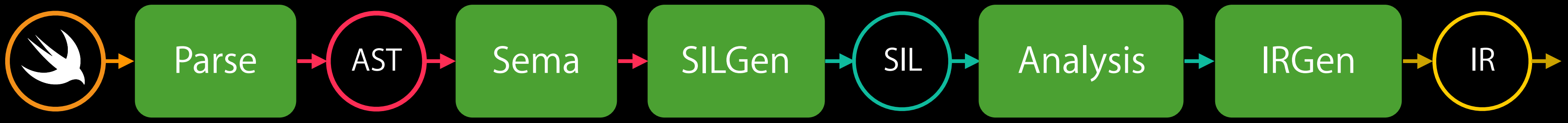

Parse → AST → Sema → SILGen → SIL → Analysis → IRGen → IR →

SIL

Fully represents program semantics

Designed for both code generation and analysis

Sits on the hot path of the compiler pipeline

Bridges the abstraction gap between source and LLVM

Design of SIL

Fibonacci

```swift
func fibonacci(lim: Int) {
  var a = 0, b = 1
  while b < lim {
    print(b)
    (a, b) = (b, a + b)
  }
}
```

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Strongly-typed IR helps validate compiler correctness

Builtins

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```
struct Int { var value: Builtin.Int64 }
struct Bool { var value: Builtin.Int1 }
func ==(lhs: Int, rhs: Int) -> Bool {
  return Bool(value: Builtin.icmp_eq_Word(lhs.value, rhs.value))
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Swift's standard library implements user-level interfaces on top of builtins

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struct Int { var value: Builtin.Int64 }
struct Bool { var value: Builtin.Int1 }
func ==(lhs: Int, rhs: Int) -> Bool {
  return Bool(value: Builtin.icmp_eq_Word(lhs.value, rhs.value))
}
```

SIL is intentionally ignorant of:

- Machine-level type layout
- Arithmetic, comparison, etc. machine-level operations

Literal Instructions

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  %lim = struct_extract %limi: $Swift.Int, #Int.value
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All instructions carry source location information for diagnostics

Especially important for numbers, which need to be statically checked for overflow

Phi Nodes?

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loop(%a: $Builtin.Int64, %b: $Builtin.Int64):
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body:
  %b1 = struct $Swift.Int (%b: $Builtin.Int64)
  apply %print(%b1) : $(Swift.Int) -> ()
  %c = builtin "add_Int64"(%a: $Builtin.Int64, %b: $Builtin.Int64): $Builtin.Int64
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Provides natural notation for conditional defs

```
entry:
  %s = invoke @mayThrowException(), label %success, label %failure
success:
  /* can only use %s here */
failure:
  %e = landingpad
```

Basic Block Arguments

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Provides natural notation for conditional defs

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success(%s):
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failure(%e):
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Fibonacci

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```

Method Lookup

```
entry(%c: $SomeClass):
  %foo = class_method %c: $SomeClass, #SomeClass.foo : $(SomeClass) -> ()
  apply %foo(%c) : $(SomeClass) -> ()
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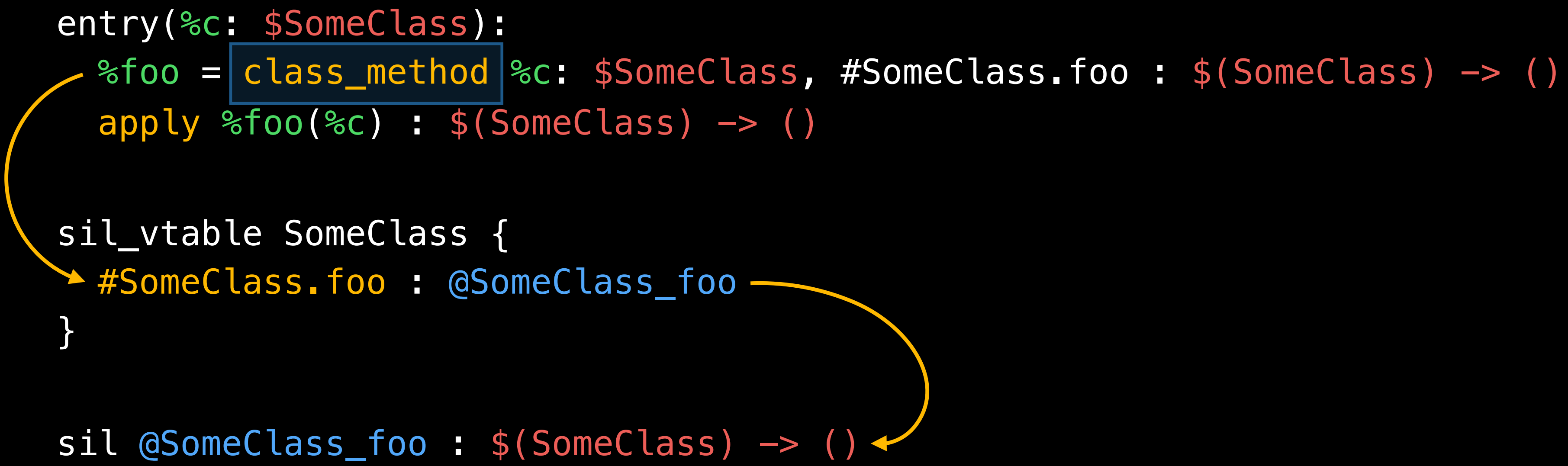
sil_vtable SomeClass {
  #SomeClass.foo : @SomeClass_foo
}
```

Method Lookup



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sil_vtable SomeClass {
  #SomeClass.foo : @SomeClass_foo
}

sil @SomeClass_foo : $(SomeClass) -> ()
```

Method Lookup

```
entry(%c: $SomeClass):
  %foo = function_ref @SomeClass_foo : $(SomeClass) -> ()
  apply %foo(%c) : $(SomeClass) -> ()
```

Method Lookup

```
entry(%x: $T, %y: $T):
  %plus = witness_method $T, #Addable.+ : $<U: Addable> (U, U) -> U
  %z = apply %plus<T>(%x, %y) : $<U: Addable> (U, U) -> U
```

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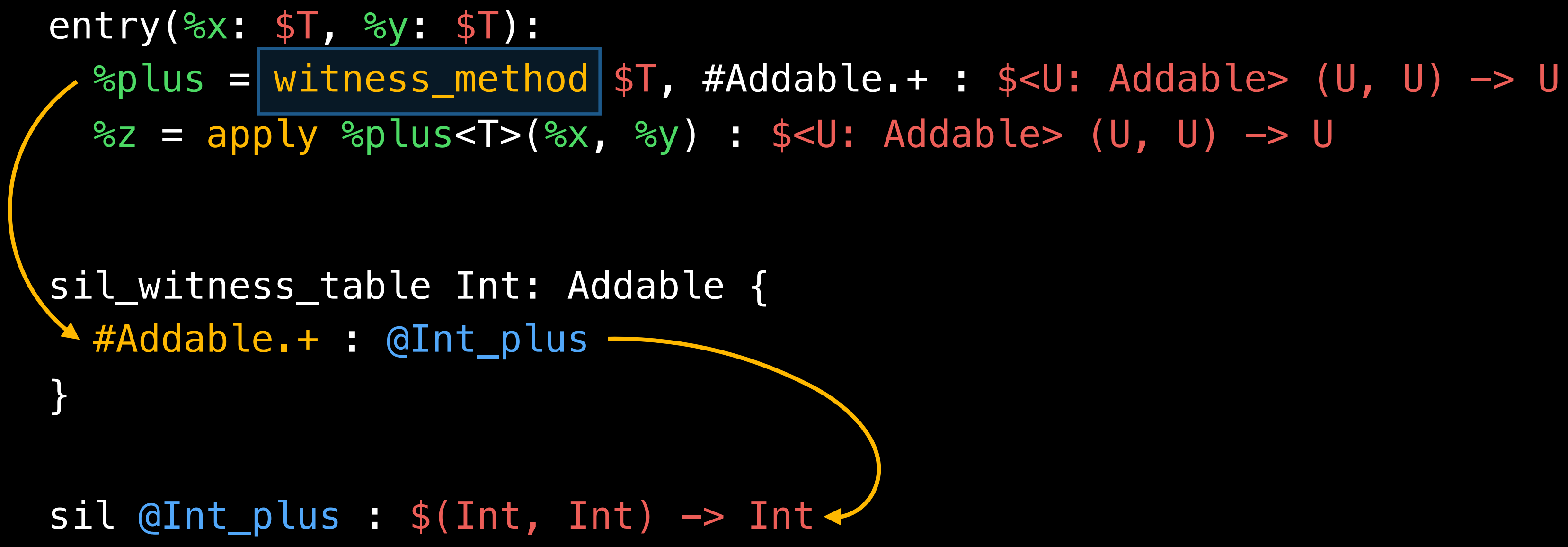
sil_witness_table Int: Addable {
  #Addable.+ : @Int_plus
}
```

Method Lookup



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sil_witness_table Int: Addable {
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}

sil @Int_plus : $(Int, Int) -> Int
```

Method Lookup

```
entry(%x: $Int, %y: $Int):
  %plus = function_ref @Int_plus : $(Int, Int) -> Int
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```

Memory Allocation

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```
%stack = alloc_stack $Int
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%stack = alloc_stack $Int
store %x to %stack: $*Int
%y = load %stack: $*Int
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%box = alloc_box $Int
```

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store %x to %stack: $*Int
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dealloc_stack %stack: $*Int

%box = alloc_box $Int

%object = alloc_ref $SomeClass
```

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%box = alloc_box $Int

%object = alloc_ref $SomeClass

strong_retain %object : $SomeClass
strong_release %object : $SomeClass
```

Control Flow

Control Flow

```
br loop
cond_br %flag: $Builtin.Int1, yes, no
return %x: $Int
unreachable
```

Control Flow

```
  br loop
  cond_br %flag: $Builtin.Int1, yes, no
  return %x: $Int
  unreachable

  switch_enum %e: $Optional<Int>, case #Optional.Some: some,
                                  case #Optional.None: none
some(%x: $Int):
```

Control Flow

```
  br loop
  cond_br %flag: $Builtin.Int1, yes, no
  return %x: $Int
  unreachable

  switch_enum %e: $Optional<Int>, case #Optional.Some: some,
                                  case #Optional.None: none
some(%x: $Int):

  checked_cast_br %c: $BaseClass, $DerivedClass, success, failure
success(%d: $DerivedClass):
```

Program Failure

Program Failure

```
%result = builtin "sadd_with_overflow_Int64"
   (%x : $Builtin.Int64, %y : $Builtin.Int64) : $(Builtin.Int64, Builtin.Int1)
%overflow = tuple_extract %result, 1
```

Program Failure

```
  %result = builtin "sadd_with_overflow_Int64"
     (%x : $Builtin.Int64, %y : $Builtin.Int64) : $(Builtin.Int64, Builtin.Int1)
  %overflow = tuple_extract %result, 1
  cond_br %overflow : $Builtin.Int1, fail, cont
cont:
  %z = tuple_extract %result, 0

  /* ... */

fail:
  builtin "int_trap"()
  unreachable
```

Program Failure

```
%result = builtin "sadd_with_overflow_Int64"
   (%x : $Builtin.Int64, %y : $Builtin.Int64) : $(Builtin.Int64, Builtin.Int1)
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%z = tuple_extract %result, 0
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%overflow = tuple_extract %result, 1

cond_fail %overflow : $Builtin.Int1
%z = tuple_extract %result, 0
```

Swift’s use of SIL

Two Phases of SIL Passes

Early SIL:

- Data flow sensitive lowering
- SSA-based diagnostics
- “Guaranteed” optimizations

Late SIL:

- Performance optimizations
- Serialization
- LLVM IRGen

Early SIL

Many individual passes:

Early SIL

Many individual passes:

- Mandatory inlining
- Capture promotion
- Box-to-stack promotion
- inout argument deshadowing
- Diagnose unreachable code
- Definitive initialization
- Guaranteed memory optimizations
- Constant folding / overflow diagnostics

Early SIL

Many individual passes:

- Mandatory inlining
- Capture promotion
- Box-to-stack promotion
- inout argument deshadowing
- Diagnose unreachable code
- Definitive initialization
- Guaranteed memory optimizations
- Constant folding / overflow diagnostics

Problems we'll look at:

- Diagnosing Overflow
- Enabling natural closure semantics with memory safety
- Removing requirement for default construction

Diagnosing Overflow

```
let v = Int8(127)+1
```

Arithmetic overflow is guaranteed to trap in Swift

- Not undefined behavior
- Not 2’s complement (unless explicitly using &+ operator)

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Arithmetic overflow is guaranteed to trap in Swift

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- Not 2’s complement (unless explicitly using &+ operator)

How can we statically diagnose overflow?

- … and produce a useful error message?

Output of SILGen

```
let v = Int8(127)+1
```

```
 %1 = integer_literal $Builtin.Int2048, 127
 %2 = function_ref @“Swift.Int8.init" : $(Builtin.Int2048) -> Int8
 %4 = apply [transparent] %2(%1) : $(Builtin.Int2048) -> Int8

 %5 = integer_literal $Builtin.Int2048, 1
 %6 = function_ref @“Swift.Int8.init" : $(Builtin.Int2048) -> Int8
 %8 = apply [transparent] %6(%5) : $(Builtin.Int2048) -> Int8

%9 = function_ref @“Swift.+” : $(Int8, Int8) -> Int8
%10 = apply [transparent] %0(%4, %8) : $(Int8, Int8) -> Int8
debug_value %10 : $Int8  // let v
```

Output of SILGen

```
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```

```
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```

After mandatory inlining

```
let v = Int8(127)+1
```

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```
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```

```
%0 = integer_literal $Builtin.Int8, 127
%4 = integer_literal $Builtin.Int8, 1
%11 = builtin "sadd_with_overflow_Int8"(%0 : $Builtin.Int8, %4 : $Builtin.Int8)

%12 = tuple_extract %11 : $(Builtin.Int8, Builtin.Int1), 1
cond_fail %12 : $Builtin.Int1

%13 = tuple_extract %11 : $(Builtin.Int8, Builtin.Int1), 0
%15 = struct $Int8 (%13 : $Builtin.Int8)
debug_value %15 : $Int8  // let v
```

After mandatory inlining

```
let v = Int8(127)+1
```

```
%0 = integer_literal $Builtin.Int8, 127
%4 = integer_literal $Builtin.Int8, 1
%11 = builtin "sadd_with_overflow_Int8"(%0 : $Builtin.Int8, %4 : $Builtin.Int8)

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After mandatory inlining

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%12 = tuple_extract %11 : $(Builtin.Int8, Builtin.Int1), 1
cond_fail %12 : $Builtin.Int1

%13 = tuple_extract %11 : $(Builtin.Int8, Builtin.Int1), 0
%15 = struct $Int8 (%13 : $Builtin.Int8)
debug_value %15 : $Int8  // let v
```

Diagnostic constant folding

```
let v = Int8(127)+1
```

```
%0 = integer_literal $Builtin.Int8, -128
%1 = integer_literal $Builtin.Int1, -1
%2 = tuple (%0 : $Builtin.Int8, %1 : $Builtin.Int1)    // folded “sadd_overflow”

cond_fail %1 : $Builtin.Int1                           // unconditional failure
```

Diagnostic constant folding

```
let v = Int8(127)+1
```

```
%0 = integer_literal $Builtin.Int8, -128
%1 = integer_literal $Builtin.Int1, -1
%2 = tuple (%0 : $Builtin.Int8, %1 : $Builtin.Int1)    // folded “sadd_overflow”

cond_fail %1 : $Builtin.Int1                           // unconditional failure
```

Diagnostic constant folding

```
let v = Int8(127)+1
```

```
%0 = integer_literal $Builtin.Int8, -128
%1 = integer_literal $Builtin.Int1, -1
%2 = tuple (%0 : $Builtin.Int8, %1 : $Builtin.Int1)    // folded “sadd_overflow”

cond_fail %1 : $Builtin.Int1                           // unconditional failure
```

Each SIL instruction maintains full location information:

- Pointer back to AST node it came from
- Including SIL inlining information

```
t.swift:2:20: error: arithmetic operation '127 + 1' (on type 'Int8') results in an overflow
  let v = Int8(127) + 1
          ~~~~~~~~~ ^ ~
```

Local variable optimization

Memory safety with closures provides challenges:

- Closures can capture references to local variables
- Closure lifetime is not limited to a stack discipline

```
func doSomething() -> Int {
  var x = 1
  takeClosure { x = 2 }
  return x
}
```

Local variable optimization

Memory safety with closures provides challenges:

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```
func doSomething() -> Int {
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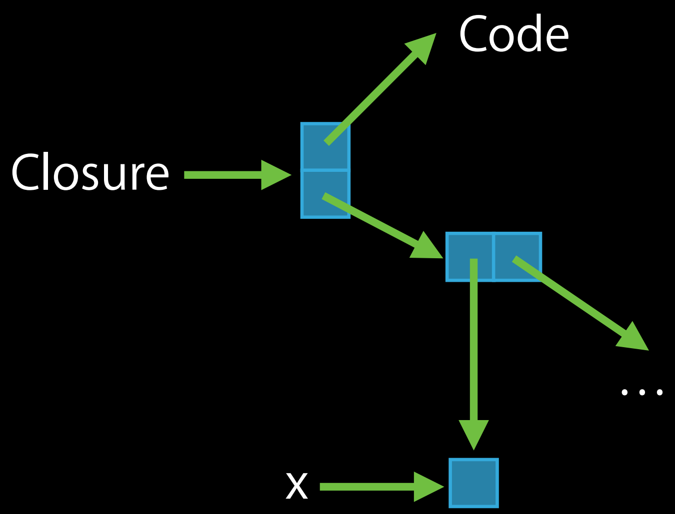

Solution:

Semantic model is for all stack variables to be on the heap

Local variables after SILGen

SILGen emits all local ‘var’iables as heap boxes with alloc_box

```
func f() -> Int {
  var x = 42

  return x
}
```

Local variables after SILGen

SILGen emits all local ‘var’iables as heap boxes with alloc_box

```
func f() -> Int {
  var x = 42

  return x
}
```

```
%0 = alloc_box $Int  // var x
%4 = ...
store %4 to %0#1 : $*Int
```

Local variables after SILGen

SILGen emits all local ‘var’iables as heap boxes with alloc_box

```
func f() -> Int {
  var x = 42

  return x
}
```

```
%0 = alloc_box $Int  // var x
%4 = ...
store %4 to %0#1 : $*Int

%6 = load %0#1 : $*Int
strong_release %0#0
return %6 : $Int
```

Local variables after SILGen

SILGen emits all local ‘var’iables as heap boxes with alloc_box

```swift
func f() -> Int {
  var x = 42

  return x
}
```

```
%0 = alloc_box $Int  // var x
%4 = ...
store %4 to %0#1 : $*Int

%6 = load %0#1 : $*Int
strong_release %0#0
return %6 : $Int
```

Box-to-stack promotes heap boxes to stack allocations

All closure captures are by reference

- Not acceptable to leave them on the heap!

Promotion eliminates byref capture

Safe to promote to by-value capture in many cases:

- … e.g. when no mutations happen after closure formation

This enables the captured value to be promoted to the stack/registers

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```
var x = …
x += 42

arr1 = arr2.map { elt in elt+x }
```

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Safe to promote to by-value capture in many cases:

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This enables the captured value to be promoted to the stack/registers

```
var x = …
x += 42

arr1 = arr2.map { elt in elt+x }
```

➡

```
var x = …
x += 42
let x2 = x
arr1 = arr2.map { elt in elt+x2 }
```

Naive SIL for by-ref closure capture

```
arr = arr.map { elt in elt+x }
```

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```
arr = arr.map { elt in elt+x }
```

```
%2 = alloc_box $Int  // var x
```

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```
arr = arr.map { elt in elt+x }
```

```
%2 = alloc_box $Int  // var x




%11 = function_ref @“Array.map” : $((Int) -> Int, Array) -> Array
%12 = apply %11(%10, %0) : $((Int) -> Int, Array) -> Array
```

Naive SIL for by-ref closure capture

```
arr = arr.map { elt in elt+x }
```

```
%2 = alloc_box $Int  // var x

%9 = function_ref @“closure1” : $(Int, @owned Builtin.NativeObject, @inout Int) -> Int
%10 = partial_apply %9(%2#0, %2#1) : $(Int, @owned Builtin.NativeObject, @inout Int) -> Int

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%12 = apply %11(%10, %0) : $((Int) -> Int, Array) -> Array



sil @“closure1” {
bb0(%0 : $Int, %1 : $Builtin.NativeObject, %2 : $*Int):
  debug_value %0 : $Int  // let elt
  %4 = load %2 : $*Int
  ...
```

Naive SIL for by-ref closure capture

```
arr = arr.map { elt in elt+x }
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  %4 = load %2 : $*Int
  ...
```

SIL after capture promotion

```
arr = arr.map { elt in elt+x }
```

```
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```

SIL after capture promotion

```
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```

```
%2 = alloc_box $Int  // var x

%4 = load %2#1 : $*Int
%7 = function_ref @“closure1” : $(Int, Int) -> Int
%10 = partial_apply %7(%4) : $(Int, Int) -> Int

%11 = function_ref @“Array.map” : $((Int) -> Int, Array) -> Array
%12 = apply %11(%10, %0) : $((Int) -> Int, Array) -> Array
```

SIL after capture promotion

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sil @“closure1” {
bb0(%0 : $Int, %1 : $Int):
  debug_value %0 : $Int  // let elt
  debug_value %1 : $Int  // var x
  ...
```

Definitive Initialization

Problem:

- Not all values can be default initialized

```
func testDI(cond : Bool) {
  var v : SomeClass

  if cond {
    v = SomeClass(1234)
  } else {
    v = SomeClass(4321)
  }

  v.foo()
}
```

Definitive Initialization

Problem:

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Desires:

- Don’t want magic numbers for primitive types
- Want to allow flexible initialization patterns

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- Dataflow driven liveness analysis

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  if cond {
    v = SomeClass(1234)
  }


  v.foo()
}
```

error: 'v' used before being initialized

Definitive Initialization Algorithm

Check each use of value to determine:

- Guaranteed initialized
- Guaranteed uninitialized
- Initialized only on some paths

```
struct Pair {
  var a, b : Int
  init() {
    a = 42
  }
}
```

Definitive Initialization Algorithm

Check each use of value to determine:

- Guaranteed initialized
- Guaranteed uninitialized
- Initialized only on some paths

Diagnostics must be great

```
struct Pair {
  var a, b : Int
  init() {
    a = 42
  }
}
```

note: 'self.b' not initialized

error: return from initializer without initializing all stored properties

DI covers many similar cases

```swift
func test() -> Float {
  var local : (Int, Float)
  local.0 = 42
  return local.1
}
```

```swift
class Base {
  init(x : Int) {}
}

class Derived : Base {
  var x, y : Int

  init() {
    x = 42; y = 1
  }
}
```

DI covers many similar cases

```
func test() -> Float {
  var local : (Int, Float)
  local.0 = 42
  return local.1
}
```

error: 'local.1' used before being initialized

```
class Base {
  init(x : Int) {}
}

class Derived : Base {
  var x, y : Int

  init() {
    x = 42; y = 1
  }
}
```

error: super.init isn't called before returning from initializer

DI Lowering: Initialization vs Assignment

```
x = y
```

Semantics depend on data flow properties

First assignment is initialization:

- Raw memory → Valid value

Subsequent assignments are replacements:

- Valid value → Valid value

DI Lowering: Initialization vs Assignment

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```
strong_retain %y : $C
store %y to %x : $*C
```

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DI Lowering: Initialization vs Assignment

```
x = y
```

Semantics depend on data flow properties

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```
strong_retain %y : $C
store %y to %x : $*C
```

Subsequent assignments are replacements:

- Valid value → Valid value

```
strong_retain %y : $C
%tmp = load %x : $*C
strong_release %tmp : $C
store %y to %x : $*C
```

Conditional Liveness

- Inherently a dataflow problem
  - Requires dynamic logic in some cases

- Conditional destruction too

```
func testDI(cond : Bool) {
  var c : SomeClass






  c = SomeClass(4321)    // init or assign?

  c.foo()
}
```

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- Inherently a dataflow problem
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  var c : SomeClass

  if cond {
    c = SomeClass(1234)
  }

  c = SomeClass(4321)    // init or assign?

  c.foo()
}
```

Language-Specific IR: Retrospective

Diagnostics

Clear improvement over Clang CFG for data flow diagnostics:

- Diagnostics always up to date as language evolves
- Great location information, source level type information
- DCE before diagnostics eliminates “false” positives

IMHO Clang should pull clang::CFG (or something better) into its IRGen path

Lowering

Nice separation between SILGen and IRGen:

- SILGen handles operational lowering
- IRGen handles type lowering & concretization of the target

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Nice separation between SILGen and IRGen:

- SILGen handles operational lowering
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Dataflow Lowering:

- Great way to handle things like swift assignment vs initialization
- Can be emulated by generating LLVM intrinsics and lowering on IR

Performance Optimizations

Necessary for generics specialization:

- Requires full source level type system
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Necessary for generics specialization:

- Requires full source level type system
- Specialization produces extreme changes to generated IR

Less clear for other optimizations

- ARC Optimization, devirt, etc could all be done on IR (with tradeoffs)

Required a ton of infrastructure:

- SILCombine
- Passmanager for analyses
- …

Summary

SIL was a lot of work, but necessary given the scope of Swift
  May make sense (or not) based on your language

We're pretty happy with it…
  …but there is still a ton of work left to do

Know LLVM and use it for what it is good for
  … don't reinvent everything just for fun :-)