Library optimizations

Unlocking High Performance in Mojo through User-Defined Dialects

Mathieu Fehr, Jeff Niu, Tobias Grosser

How does clang optimize uses of the stdlib?

```cpp
void foo() {
    std::string a = "A long long long long string";
}
```

```cpp
int bar(std::vector<int>& v) {
  v.push_back(42);
  int res = v.back();
  v.pop_back();
  return res;
}
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}
```

```cpp
void foo() {
}
```

```asm
foo():
        push    rbx
        sub     rsp, 48
        lea     rbx, [rsp + 32]
        mov     qword ptr [rsp + 16], rbx
        mov     qword ptr [rsp + 8], 28
        lea     rdi, [rsp + 16]
        lea     rsi, [rsp + 8]
        xor     edx, edx
        call    std::__cxx11::basic_string<char, std::char_traits<char>, std::allocator<char>>
                    ::_M_create(unsigned long&, unsigned long)@PLT
        mov     qword ptr [rsp + 16], rax
        mov     rcx, qword ptr [rsp + 8]
        mov     qword ptr [rsp + 32], rcx
        movups  xmm0, xmmword ptr [rip + .L.str+12]
        movups  xmmword ptr [rax + 12], xmm0
        movups  xmm0, xmmword ptr [rip + .L.str]
        movups  xmmword ptr [rax], xmm0
        mov     qword ptr [rsp + 24], rcx
        mov     rax, qword ptr [rsp + 16]
        mov     byte ptr [rax + rcx], 0
        mov     rdi, qword ptr [rsp + 16]
        cmp     rdi, rbx
        je      .LBB0_2
        mov     rsi, qword ptr [rsp + 32]
        inc     rsi
        call    operator delete(void*, unsigned long)@PLT
.LBB0_2:
        add     rsp, 48
        pop     rbx
        ret

.L.str:
        .asciz  "A long long long long string"
```

How does clang optimize uses of the stdlib?

```
void foo() {
    std::string a = "A long long long long string";
}
```

↓

```
void foo() {
}
```

This call could do anything

COMPILER EXPLORER

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foo():
        push    rbx
        sub     rsp, 48
        lea     rbx, [rsp + 32]
        mov     qword ptr [rsp + 16], rbx
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        mov     rcx, qword ptr [rsp + 8]
        mov     qword ptr [rsp + 32], rcx
        movups  xmm0, xmmword ptr [rip + .L.str+12]
        movups  xmmword ptr [rax + 12], xmm0
        movups  xmm0, xmmword ptr [rip + .L.str]
        movups  xmmword ptr [rax], xmm0
        mov     qword ptr [rsp + 24], rcx
        mov     rax, qword ptr [rsp + 16]
        mov     byte ptr [rax + rcx], 0
        mov     rdi, qword ptr [rsp + 16]
        cmp     rdi, rbx
        je      .LBB0_2
        mov     rsi, qword ptr [rsp + 32]
        inc     rsi
        call    operator delete(void*, unsigned long)@PLT
.LBB0_2:
        add     rsp, 48
        pop     rbx
        ret

.L.str:
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```

How does clang optimize uses of the stdlib?

```
foo():
        ret
```

```
void foo() {
    std::string a = "A long long long long string";
}
```

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void foo() {
}
```

How does clang optimize uses of the stdlib?

```
int bar(std::vector<int>& v) {
  v.push_back(42);
  int res = v.back();
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⬇

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int bar(std::vector<int>& v) {
  v.push_back(42);
  v.pop_back();
  return 42;
}
```

How does clang optimize uses of the stdlib?

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  v.pop_back();
  return res;
}
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⬇

```cpp
int bar(std::vector<int>& v) {
  return 42;
}
```

How does clang optimize uses of the stdlib?

```cpp
int bar(std::vector<int>& v) {
  v.push_back(42);
  int res = v.back();
  v.pop_back();
  return res;
}
```

```cpp
int bar(std::vector<int>& v) {
  return 42;
}
```

```asm
bar(std::vector<int, std::allocator<int>>&):
        push    r15
        push    r14
        push    r13
        push    r12
        push    rbx
        mov     rbx, qword ptr [rdi + 8]
        cmp     rbx, qword ptr [rdi + 16]
        je      .LBB0_2
        mov     dword ptr [rbx], 42
        jmp     .LBB0_8
.LBB0_2:
        mov     r14, qword ptr [rdi]
        sub     rbx, r14
        movabs  rax, 9223372036854775804
        cmp     rbx, rax
        je      .LBB0_9
        mov     r12, rdi
        mov     rax, rbx
        sar     rax, 2
        cmp     rax, 1
        mov     rcx, rax
        adc     rcx, 0
        lea     r13, [rcx + rax]
        movabs  rdx, 2305843009213693951
        cmp     r13, rdx
        cmovae  r13, rdx
        add     rcx, rax
        cmovb   r13, rdx
        lea     rdi, [4*r13]
        call    operator new(unsigned long)@PLT
        mov     r15, rax
        mov     dword ptr [rax + rbx], 42
        test    rbx, rbx
        jle     .LBB0_5
        mov     rdi, r15
        mov     rsi, r14
        mov     rdx, rbx
        call    memcpy@PLT
.LBB0_5:
        test    r14, r14
        je      .LBB0_7
        mov     rdi, r14
        mov     rsi, rbx
        call    operator delete(void*, unsigned long)@PLT
.LBB0_7:
        add     rbx, r15
        mov     rdi, r12
        mov     qword ptr [r12], r15
        lea     rax, [r15 + 4*r13]
        mov     qword ptr [r12 + 16], rax
.LBB0_8:
        mov     eax, dword ptr [rbx]
        mov     qword ptr [rdi + 8], rbx
        pop     rbx
        pop     r12
        pop     r13
        pop     r14
        pop     r15
        ret
.LBB0_9:
        lea     rdi, [rip + .L.str]
        call    std::__throw_length_error(char const*)@PLT

.L.str:
        .asciz  "vector::_M_realloc_append"
```

How does clang optimize uses of the stdlib?

```cpp
int bar(std::vector<int>& v) {
  v.push_back(42);
  int res = v.back();
  v.pop_back();
  return res;
}
```

```cpp
int bar(std::vector<int>& v) {
  return 42;
}
```

```cpp
int bar(std::vector<int>& v) {
  if (v.capacity() == v.size())
    v.double_capacity();
  return res;
}
```

How does clang optimize uses of the stdlib?

```
int bar(std::vector<int>& v) {
  v.push_back(42);
  int res = v.back();
  v.pop_back();
  return res;
}
```

```
int bar(std::vector<int>& v) {
  return 42;
}
```

```
int bar(std::vector<int>& v) {
  if (v.capacity() == v.size())
    v.double_capacity();
  return res;
}
```

Cannot be optimized away even when inlined

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```
int bar(std::vector<int>& v) {
  v.push_back(42);
  int res = v.back();
  v.pop_back();
  return res;
}
```

```
int bar(std::vector<int>& v) {
  return 42;
}
```

ILLEGAL

```
int bar(std::vector<int>& v) {
  if (v.capacity() == v.size())
    v.double_capacity();
  return res;
}
```

Cannot be optimized away even when inlined

Many potentially illegal optimization opportunities

```
if (!hm.contains(x))
  hm[x] = 42;
```

Many potentially illegal optimization opportunities

Many potentially illegal optimization opportunities

```
hm.try_emplace(x, 42)
```

```
x * y + z
```

Many potentially illegal optimization opportunities

```
hm.try_emplace(x, 42)
```

```
fma(x, y, z)
```

Many potentially illegal optimization opportunities

```
hm.try_emplace(x, 42)
```

```
fma(x, y, z)
```

```
sort(v.begin(), v.end());
auto it = find(v.begin(), v.end(), x);
bool x = it != v.end();
```

Many potentially illegal optimization opportunities

```
hm.try_emplace(x, 42)
```

```
fma(x, y, z)
```

```
sort(v.begin(), v.end());
bool x = binary_search(v.begin(), v.end(), x);
```

Many potentially illegal optimization opportunities

```
hm.try_emplace(x, 42)
```

```
fma(x, y, z)
```

```
sort(v.begin(), v.end());
bool x = binary_search(v.begin(), v.end(), x);
```

```
for (int i = 0; i < N; i++)
    v.push_back(i)
```

Many potentially illegal optimization opportunities

```
hm.try_emplace(x, 42)
```

```
fma(x, y, z)
```

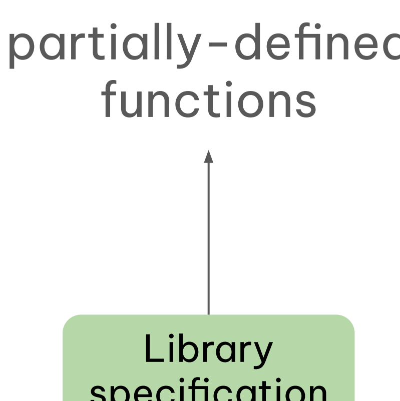
```
sort(v.begin(), v.end());
bool x = binary_search(v.begin(), v.end(), x);
```

```
v.reserve(v.size() + N);
for (int i = 0; i < N; i++)
   v.push_back(i)
```

Information is lost too early

Library specification

Information is lost too early



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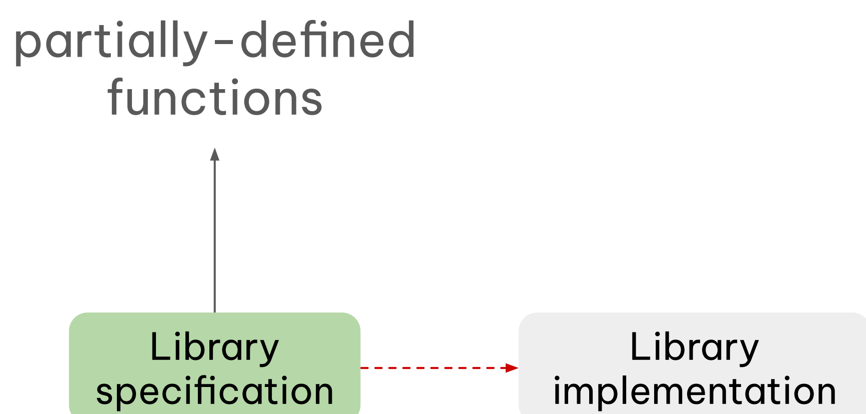

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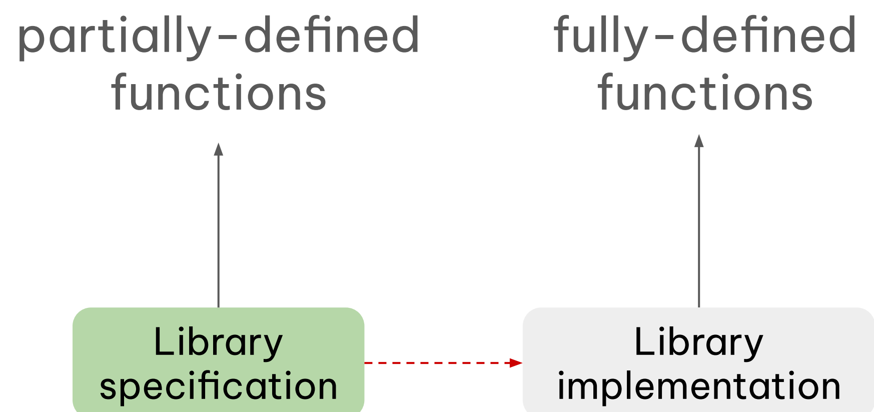

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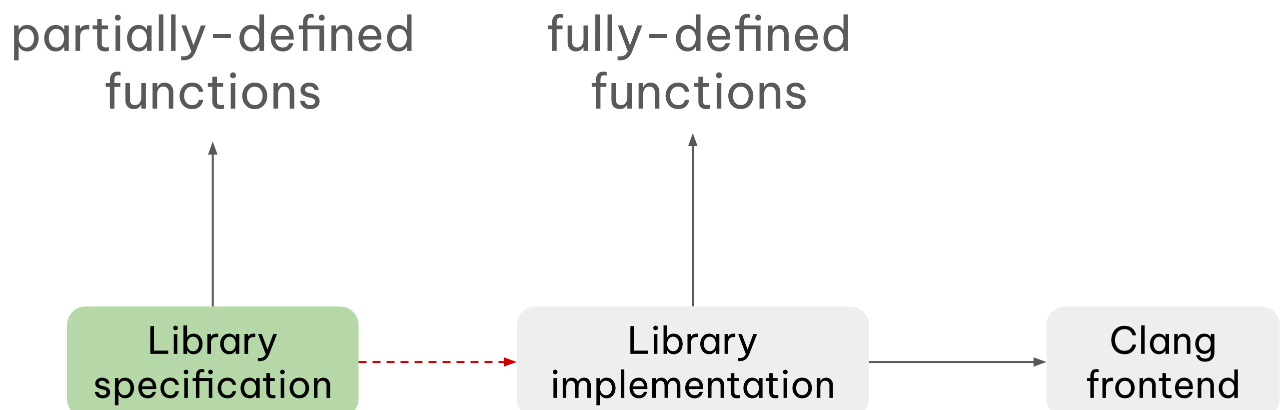

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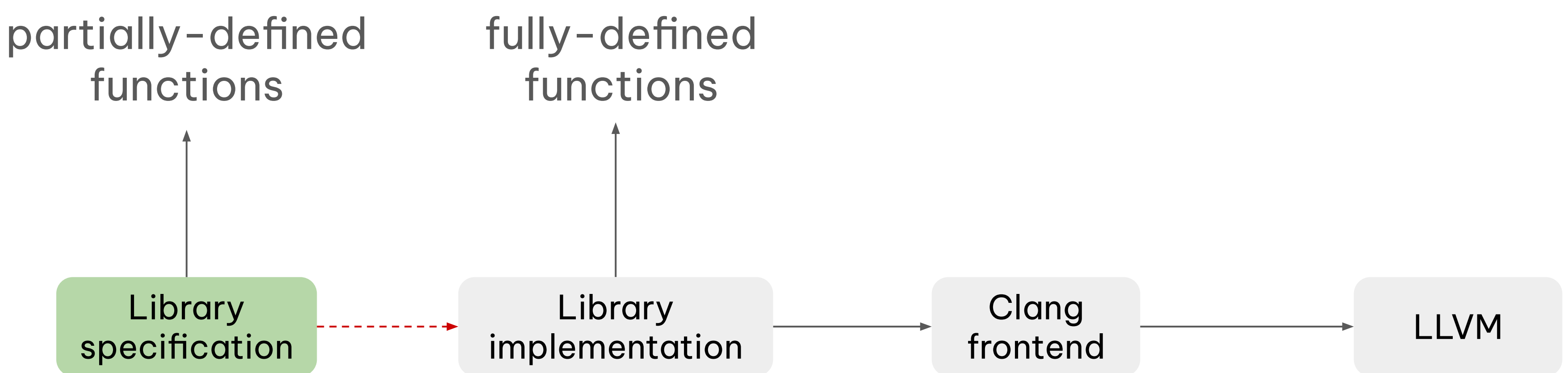

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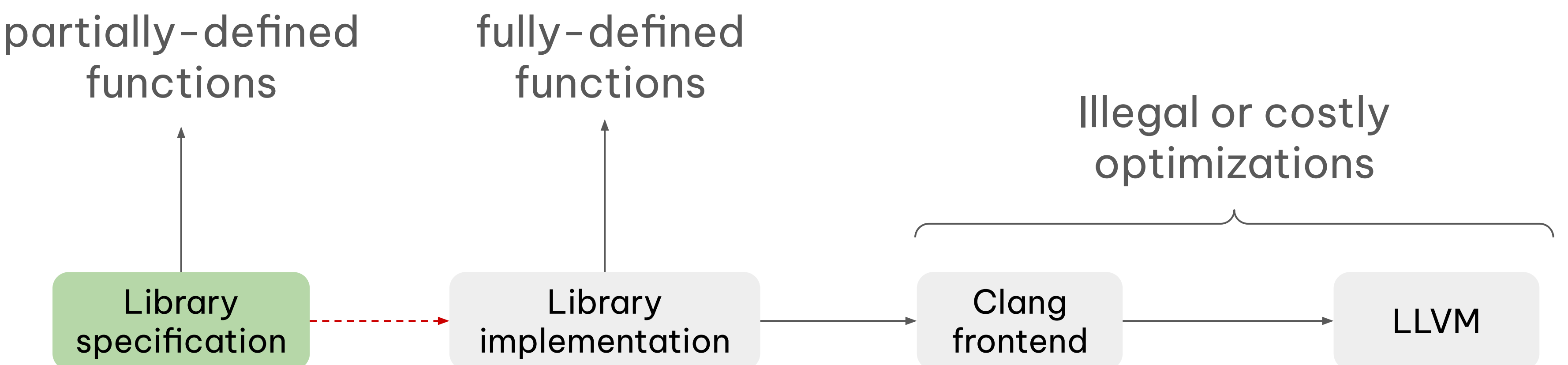

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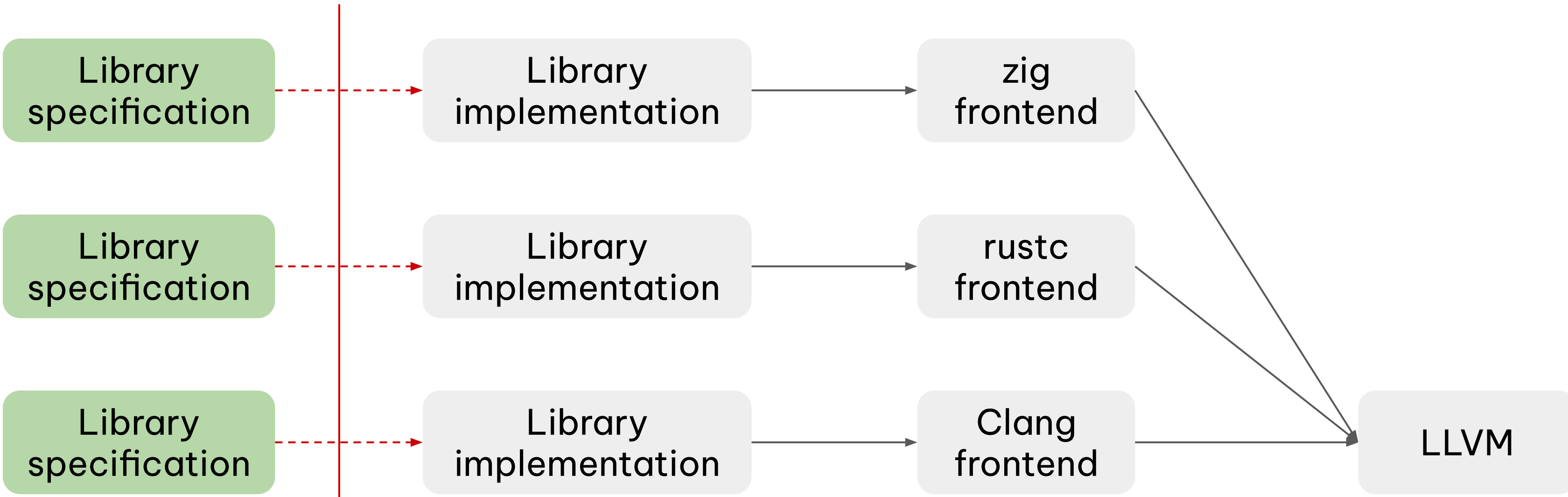

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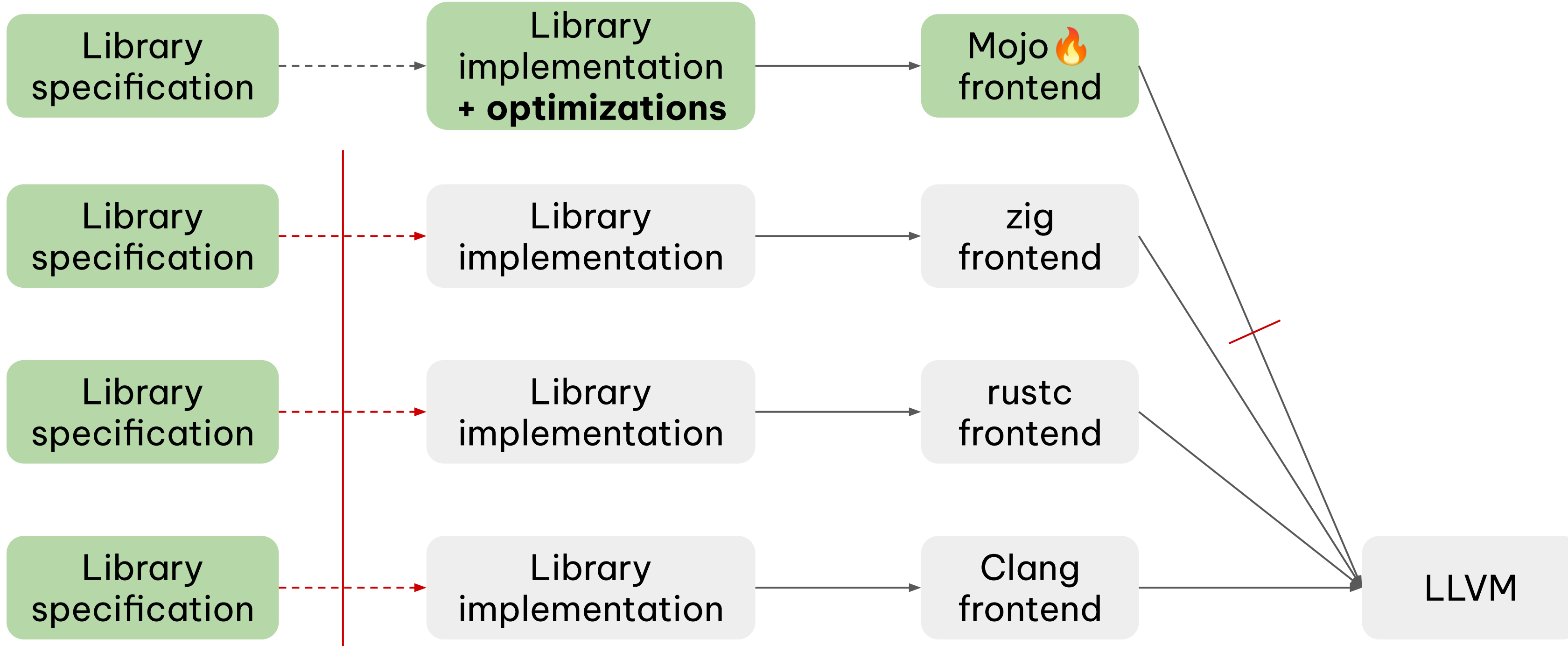

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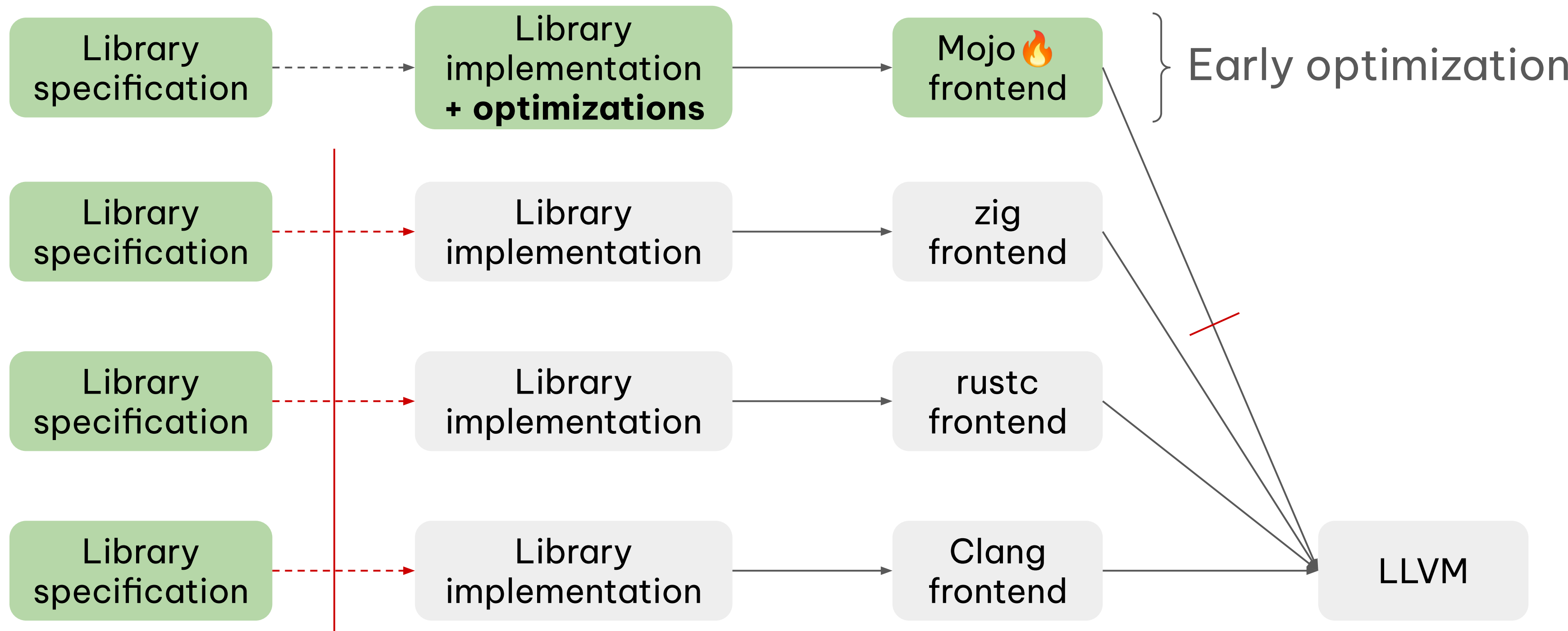

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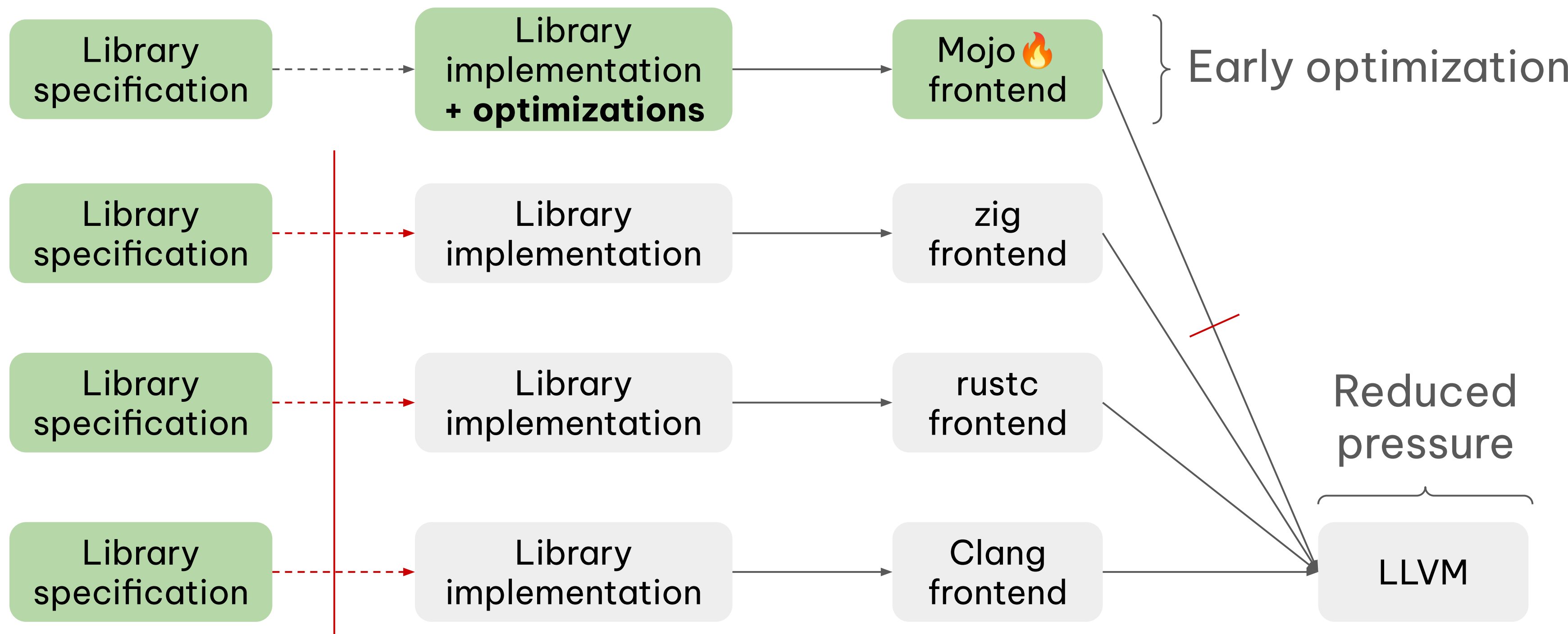

How can we solve this problem in Mojo🔥?

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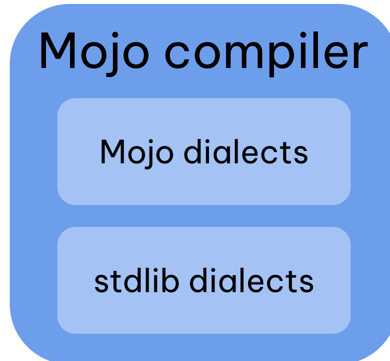

How can we solve this problem in Mojo ?

Doesn't scale well

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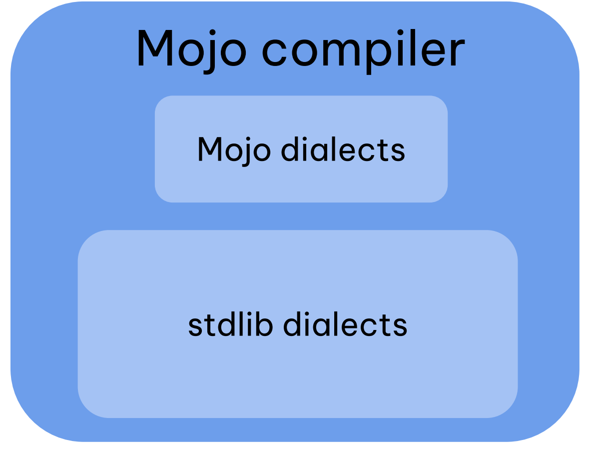


Doesn't scale well

Complexifies the compiler

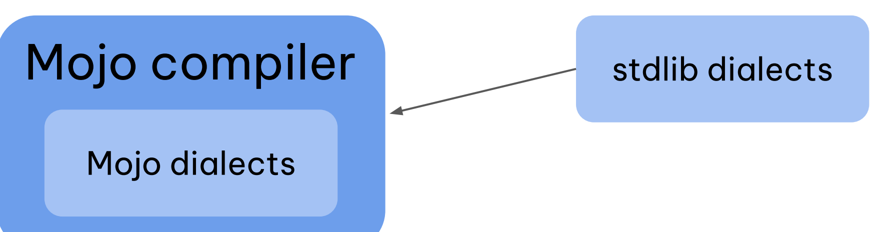
How can we solve this problem in Mojo ?

Doesn't scale well

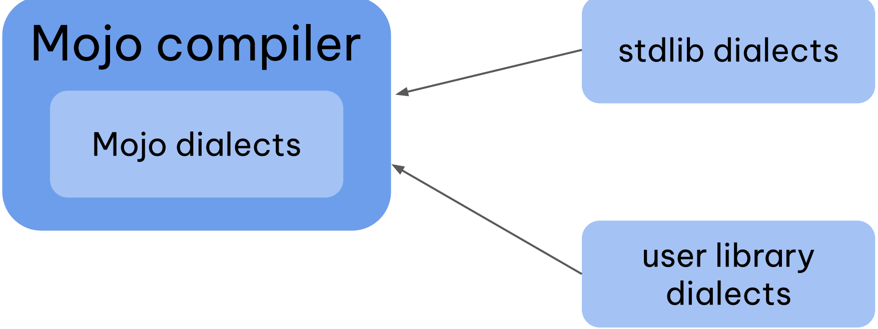
Complexifies the compiler

Doesn't generalize to user libraries

How can we solve this problem in Mojo🔥?



How can we solve this problem in Mojo ?



Anatomy of a custom op in Mojo🔥

```
fn mul_two(x: Int32) -> Int32:
    return x * 2
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- Sufficient for all the cases we presented

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    return x * 2
```

- Familiar for Mojo users
- No need to learn C++/ODS/TableGen
- Sufficient for all the cases we presented
- Very few changes required in the compiler

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Functions encode:
- A verifier

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Functions encode:
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- A lowering

Anatomy of a custom op in Mojo🔥

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Functions encode:

- A verifier
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Anatomy of a custom op in Mojo🔥

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fn mul_two(x: Int32) -> Int32:
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```

Functions encode:

- A verifier
- A lowering
- An interpreter
- A few interfaces (side effects)

Anatomy of a custom optimization in Mojo🔥

```
@custom_op
fn mul_two(x: Int32) -> Int32:
    return x * 2


@custom_op(add_mul_two)
fn add(x: Int32, y: Int32) -> Int32:
    return x + y
```

Anatomy of a custom optimization in Mojo🔥

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```
fn add_mul_two(inout op: Operation,
               inout b: Rewriter) -> Bool:
```

"Canonicalization patterns"

Anatomy of a custom optimization in Mojo🔥

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```

```
fn add_mul_two(inout op: Operation,
               inout b: Rewriter) -> Bool:
    var loc = op.location()
    if op.operand(0) != op.operand(1):
        return True

    var new_op = Op[mul_two](
        loc,
        operands=List[Value](op.operand(0))
        results=List[Type](op.result(0).type()),
        params=op.get_attr("params"),
    )
    _ = b.insert(new_op)
    b.replace_op_with(op, new_op)
    return True
```

Anatomy of a custom optimization in Mojo🔥

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@custom_op
fn mul_two(x: Int32) -> Int32:
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MLIR Mojo API

Anatomy of a custom optimization in Mojo🔥

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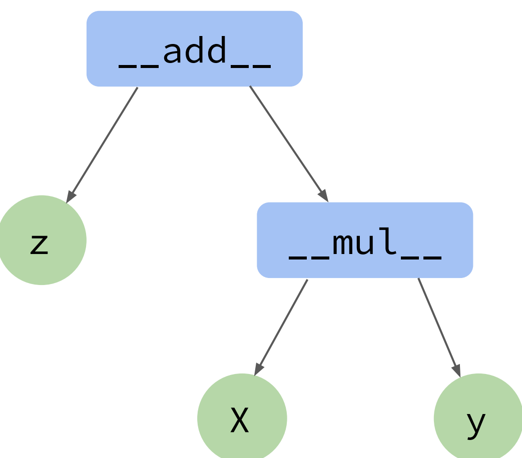
        loc,
        operands=List[Value](op.operand(0))
        results=List[Type](op.result(0).type()),
        params=op.get_attr("params"),
    )
    _ = b.insert(new_op)
    b.replace_op_with(op, new_op)
    return True
```

We reference the functions directly

Handling memory-based optimizations

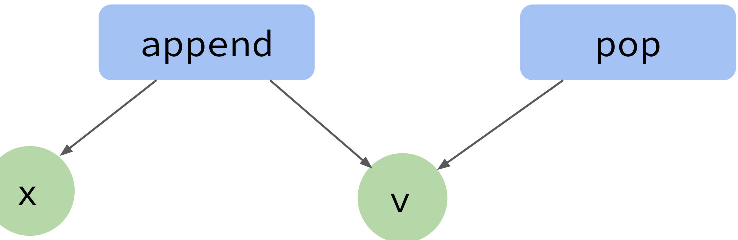
`z + x * y`



Handling memory-based optimizations

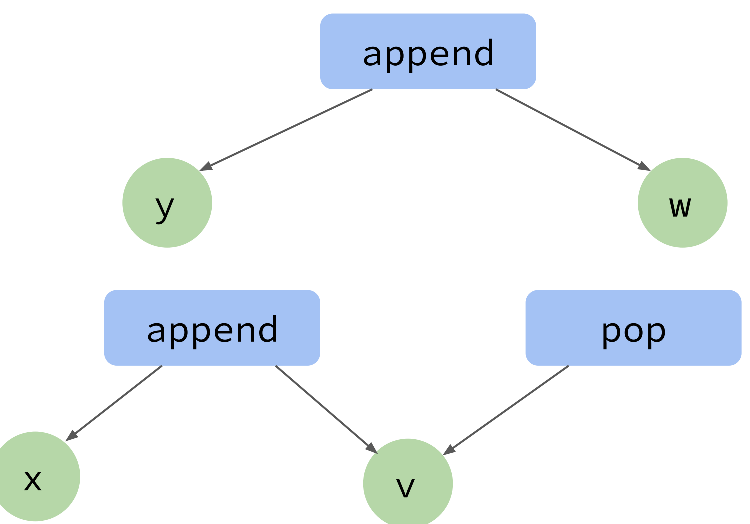
```
v.append(x)

v.pop()
```



Handling memory-based optimizations

```
v.append(x)
w.append(y)
v.pop()
```



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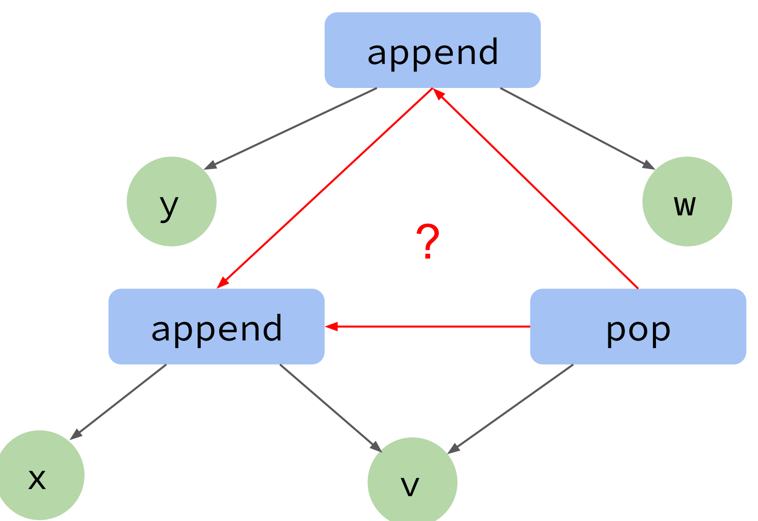
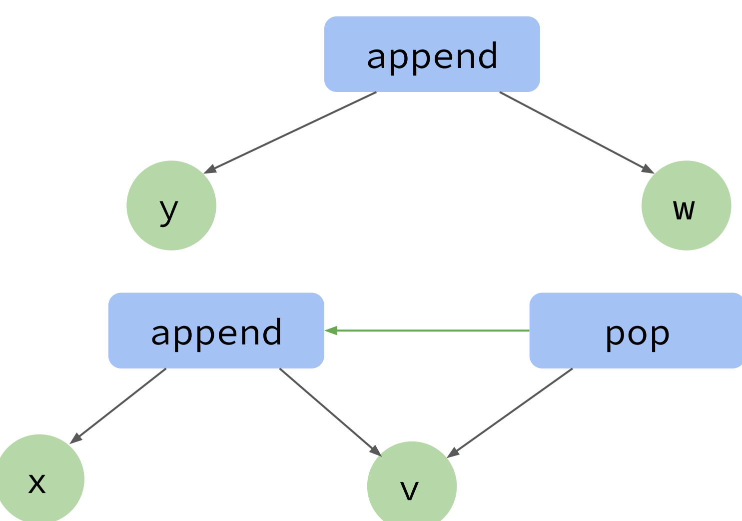


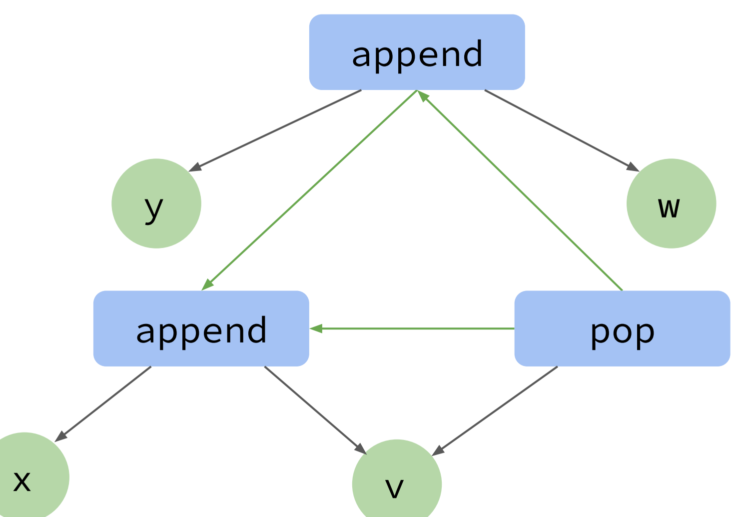
Handling memory-based optimizations with memorySSA

```
v.append(x)
w.append(y) # no alias
v.pop()
```

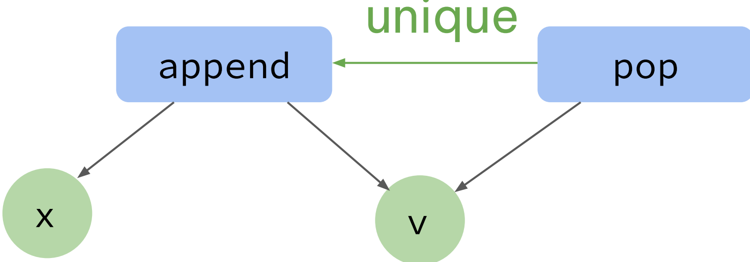


Handling memory-based optimizations with memorySSA

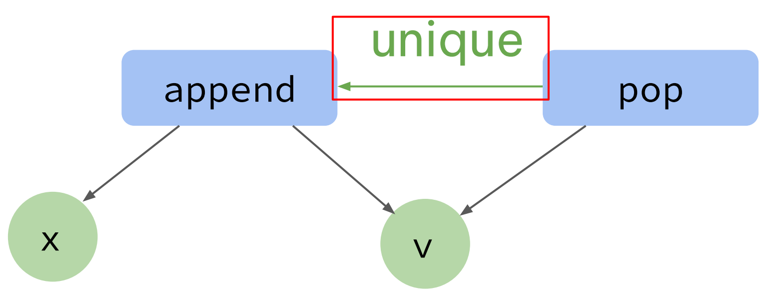
```
v.append(x)
w.append(y) # may alias
v.pop()
```



Optimizing the append/pop example



Optimizing the append/pop example

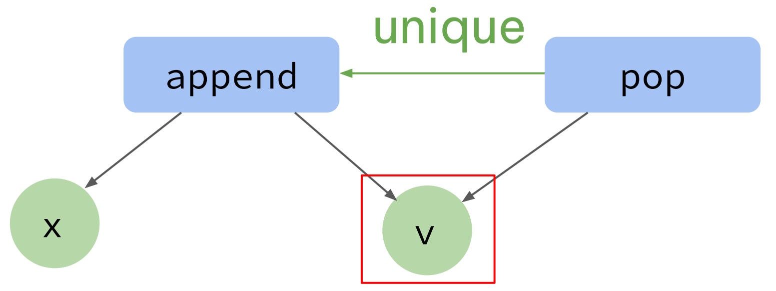



```
fn append_pop(inout op: Operation,
              inout r: Rewriter) -> Bool:
  var memoryssa = r.get_memoryssa()
  var append =
    memoryssa.get_unique_predecessor[Op[List.append]](op)
  if not append:
    return True

  if append.operands[0] != op.operands[0]:
    return True

  rewriter.erase_op(append)
  rewriter.replace_op(op, op.operands[1])
  return True
```

Optimizing the append/pop example

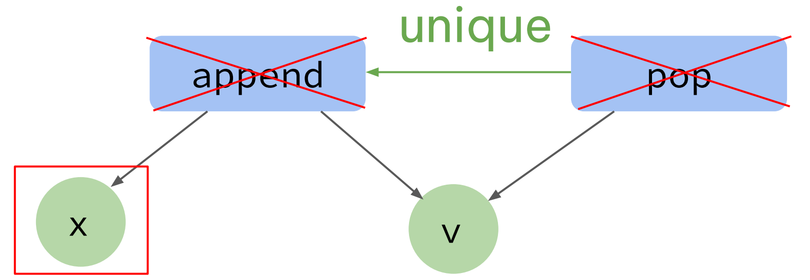



```
fn append_pop(inout op: Operation,
              inout r: Rewriter) -> Bool:
  var memoryssa = r.get_memoryssa()
  var append =
    memoryssa.get_unique_predecessor[Op[List.append]](op)
  if not append:
    return True

  if append.operands[0] != op.operands[0]:
    return True

  rewriter.erase_op(append)
  rewriter.replace_op(op, op.operands[1])
  return True
```

Optimizing the append/pop example




```
fn append_pop(inout op: Operation,
              inout r: Rewriter) -> Bool:
  var memoryssa = r.get_memoryssa()
  var append =
    memoryssa.get_unique_predecessor[Op[List.append]](op)
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  if append.operands[0] != op.operands[0]:
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  rewriter.erase_op(append)
  rewriter.replace_op(op, op.operands[1])
  return True
```

Optimizing the string example

Optimizing the string example

__init__ ← unique — __del__

```
fn string_init(inout op: Operation,
               inout r: Rewriter) -> Bool:
  var memoryssa = r.get_memoryssa()
  var del =
    memoryssa.get_unique_successor[Op[List.__del__]](op)

  if not del:
    return True
  if del.operands(0) != op.operands(0):
    return True

  rewriter.erase_op(op)
  rewriter.erase_op(del)
  return True
```

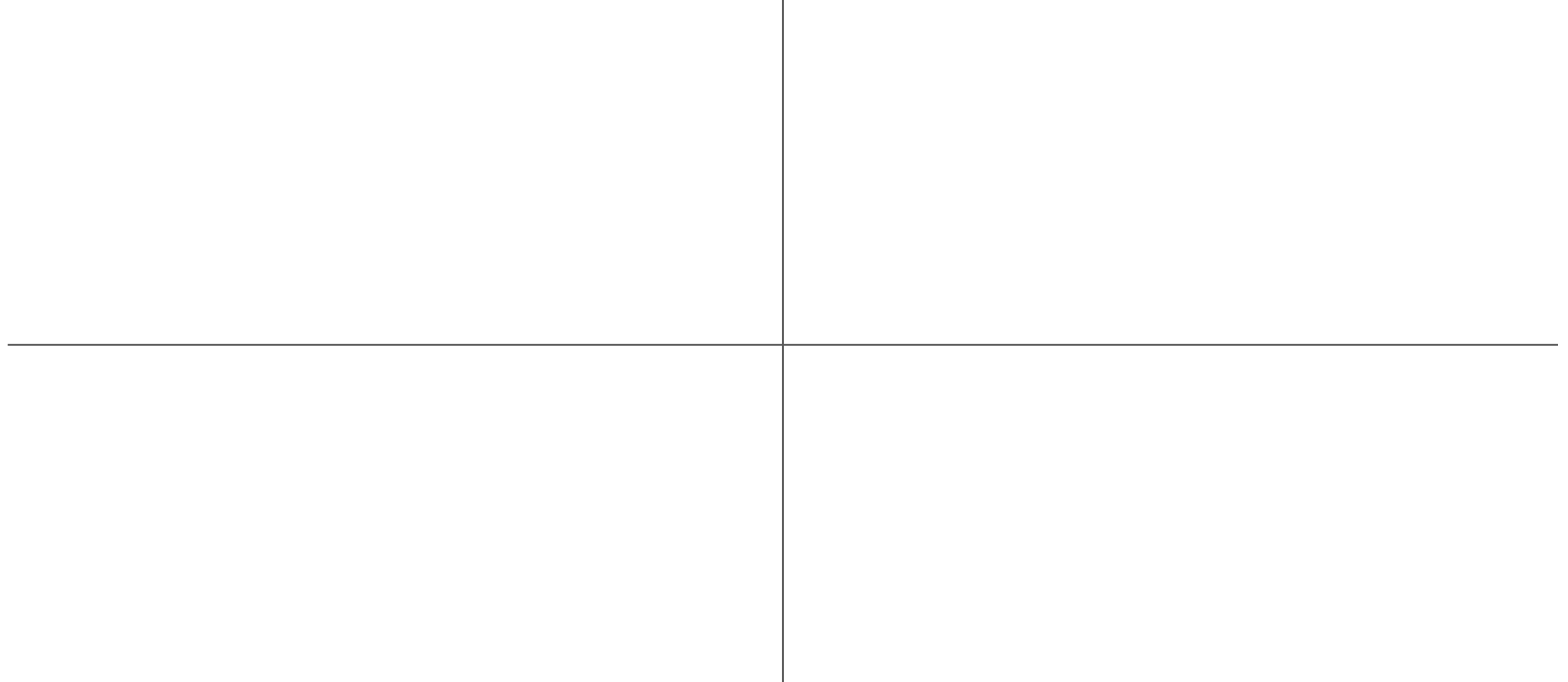
Optimizing the string example

```
fn string_init(inout op: Operation,
               inout r: Rewriter) -> Bool:
  var memoryssa = r.get_memoryssa()
  var del =
    memoryssa.get_unique_successor[Op[List.__del__]](op)

  if not del:
    return True
  if del.operands(0) != op.operands(0):
    return True

  rewriter.erase_op(op)
  rewriter.erase_op(del)
  return True
```

Conclusion

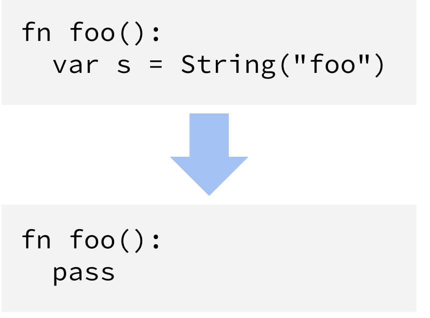


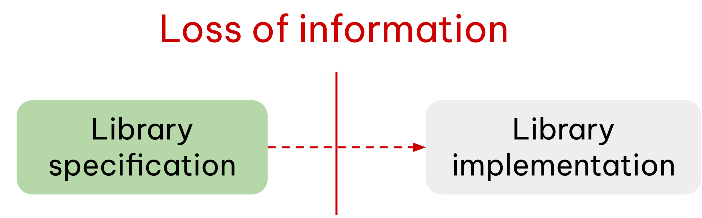
Conclusion

```
fn foo():
  var s = String("foo")
```

```
fn foo():
  pass
```

Conclusion

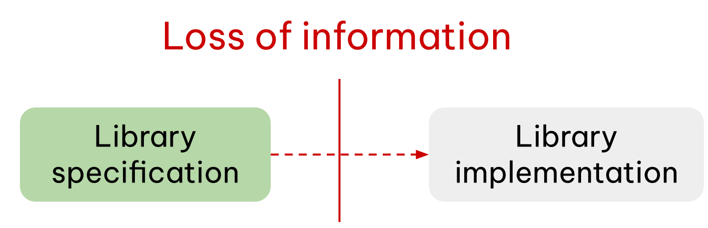




Conclusion

```
fn foo():
  var s = String("foo")
```

```
fn foo():
  pass
```

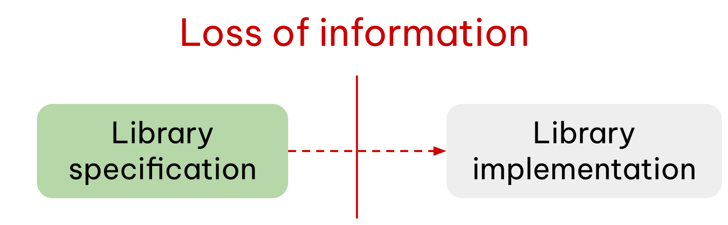



```
class String:
  @custom_op(string_init)
  fn __init__(inout self, x: StringLiteral):
    ...
```

Conclusion

```
fn foo():
  var s = String("foo")
```

```
fn foo():
  pass
```




```
class String:
  @custom_op(string_init)
  fn __init__(inout self, x: StringLiteral):
    ...
```