Debug Information

From Metadata to Modules

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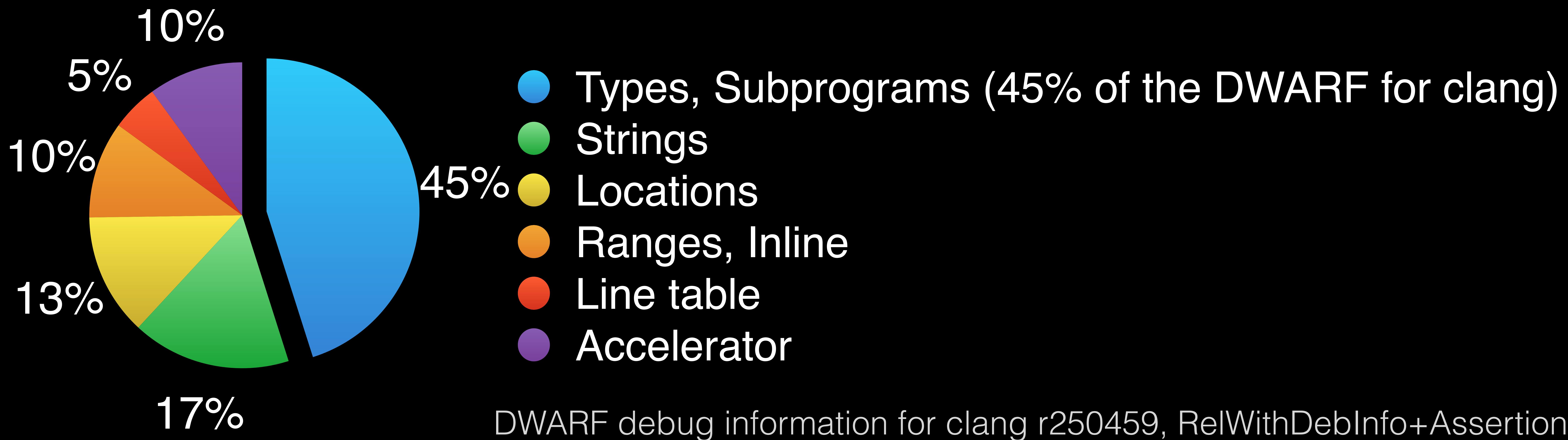
What **is** Debug Information?

- provides a mapping from **source code** → **binary program**
- on disk: as DWARF, a highly compressed format
- in LLVM: as metadata (pre-finalized DWARF)



DWARF debug information for clang r250459, RelWithDebInfo+Assertions

Debug Info, Scalability, and LTO

- volume of debug info limits scalability of the compiler, particularly when using LTO

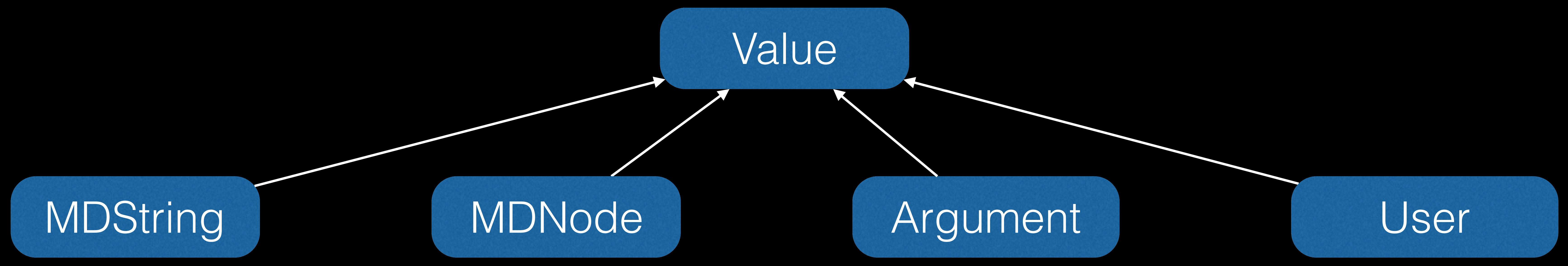
- we attacked this problem from two sides:
  - **LLVM**: efficient new **Metadata** representation
  - **Clang**: emit less debug info with **Module Debugging**

LLVM: efficient new Metadata representation

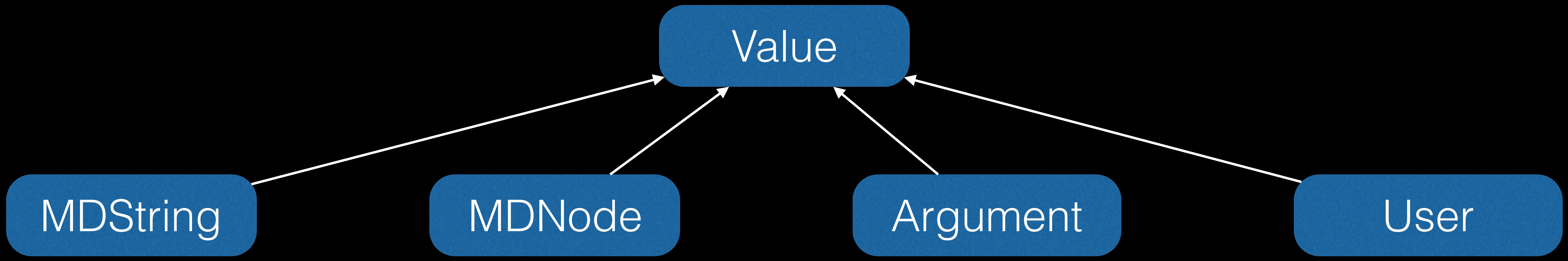
- making Metadata lightweight: dropping use-lists and separating from Value
- specialized MDNodes: syntax, **isa** support, and memory footprint
- constructing Metadata graphs efficiently and **distinct** Metadata
- grab bag of other major LTO optimizations

Making Metadata lightweight

old class hierarchy



How do operands work?



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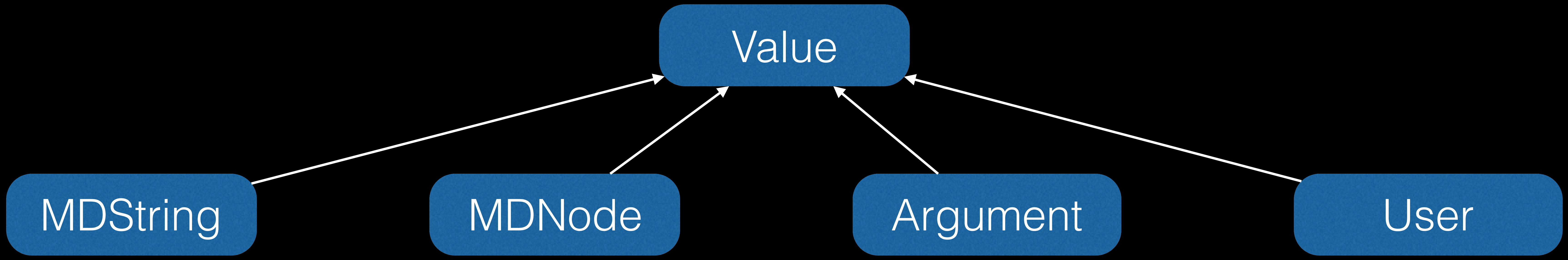
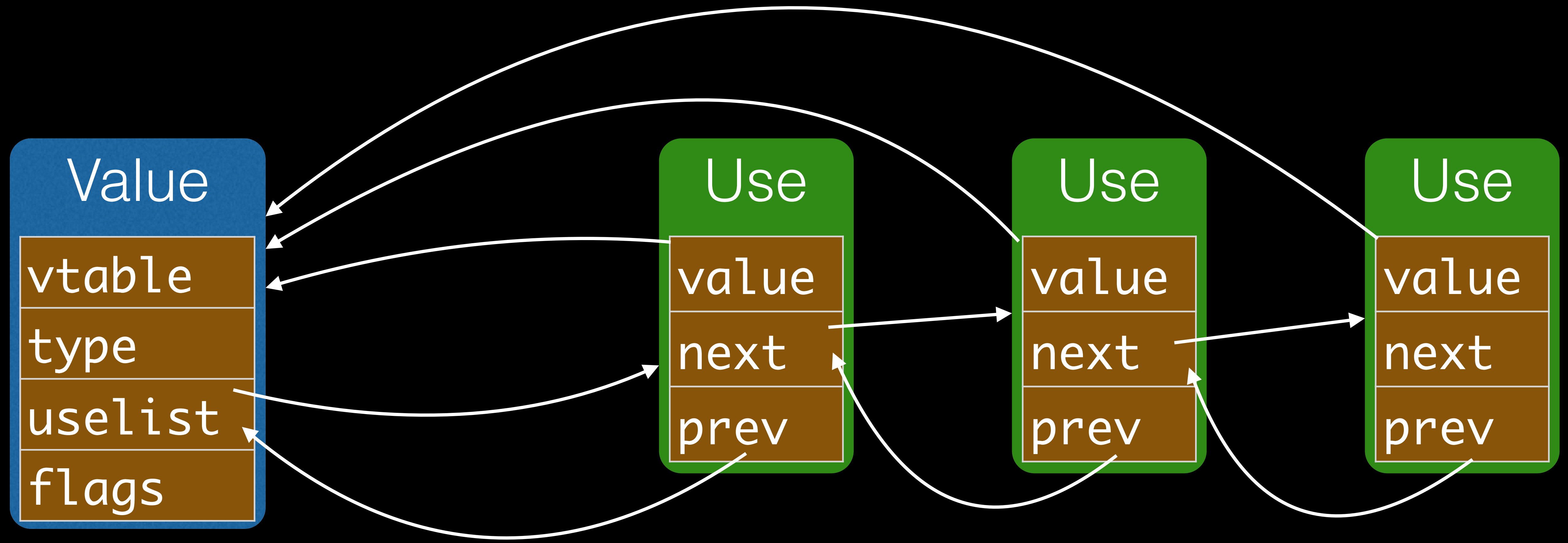


intrusive storage for use-lists



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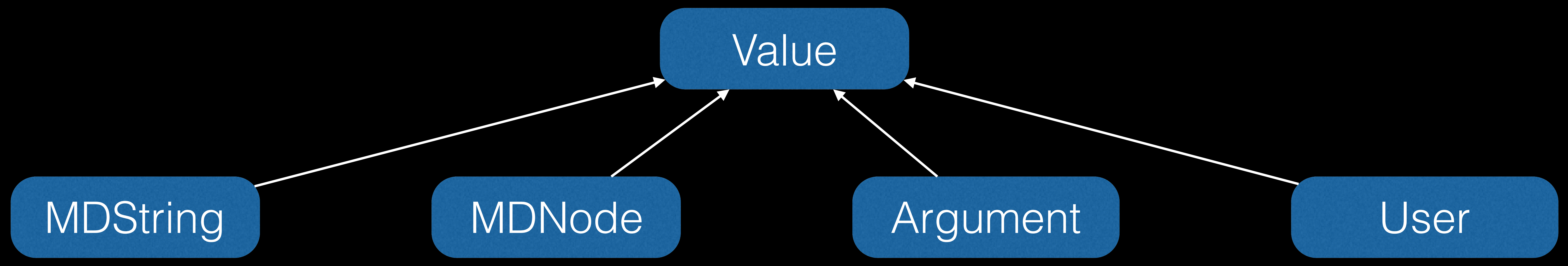
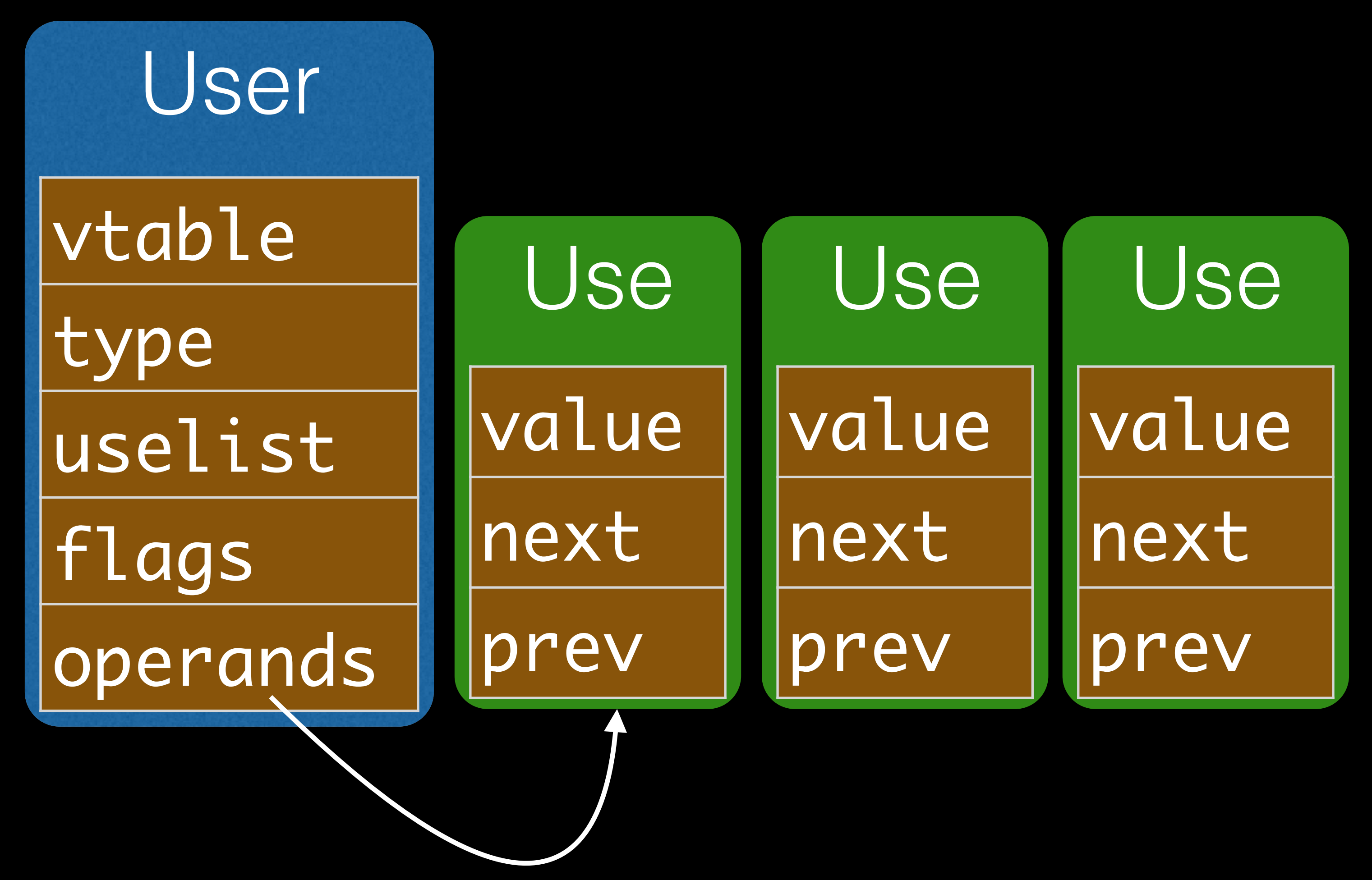


User operands are an array of Uses



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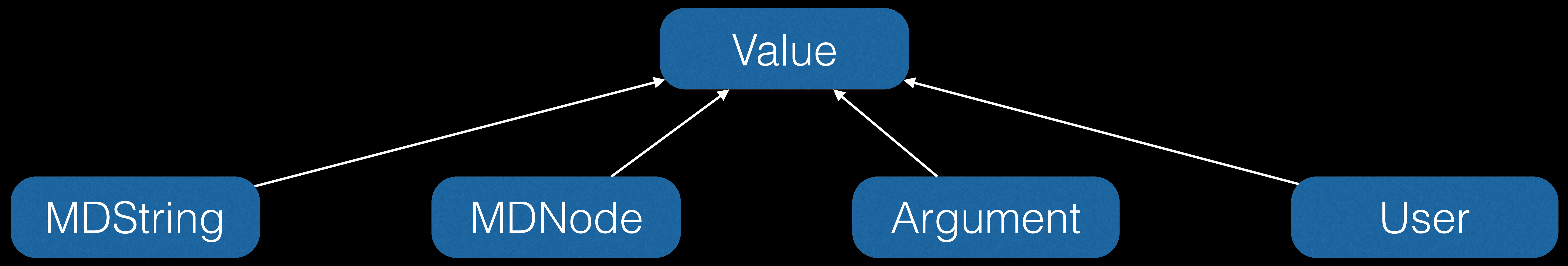
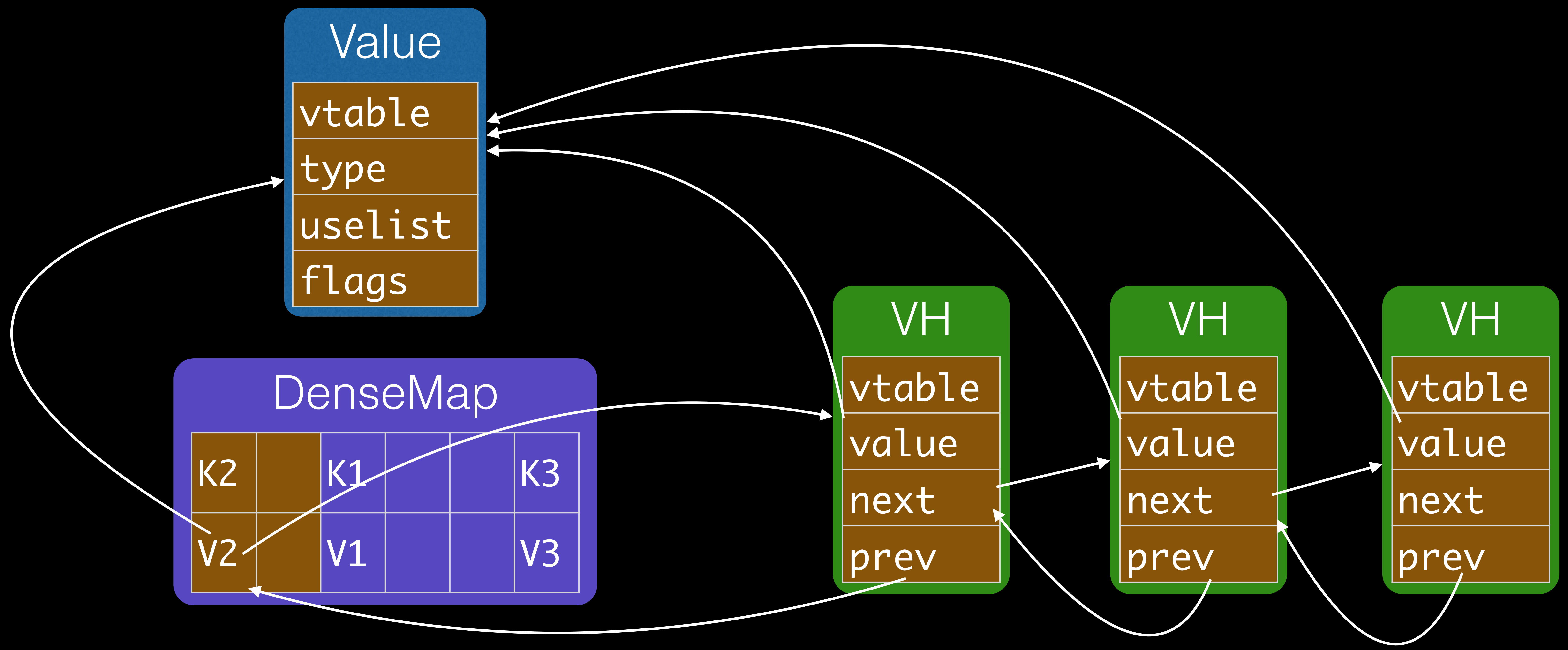
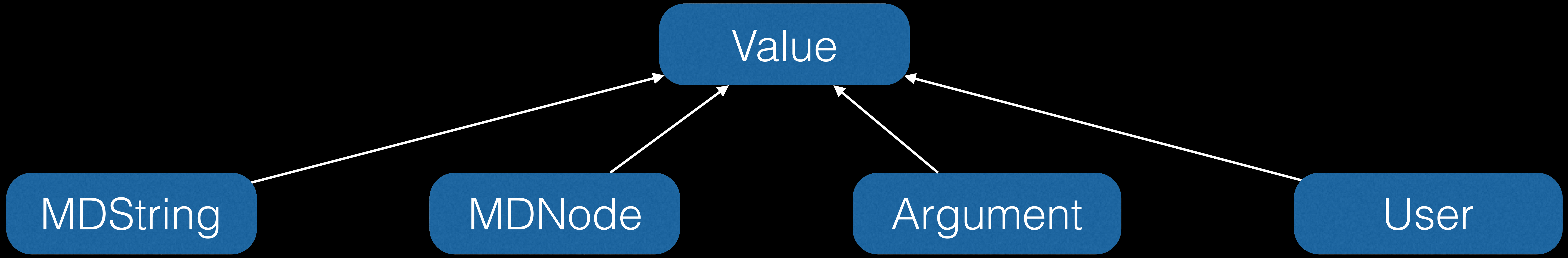


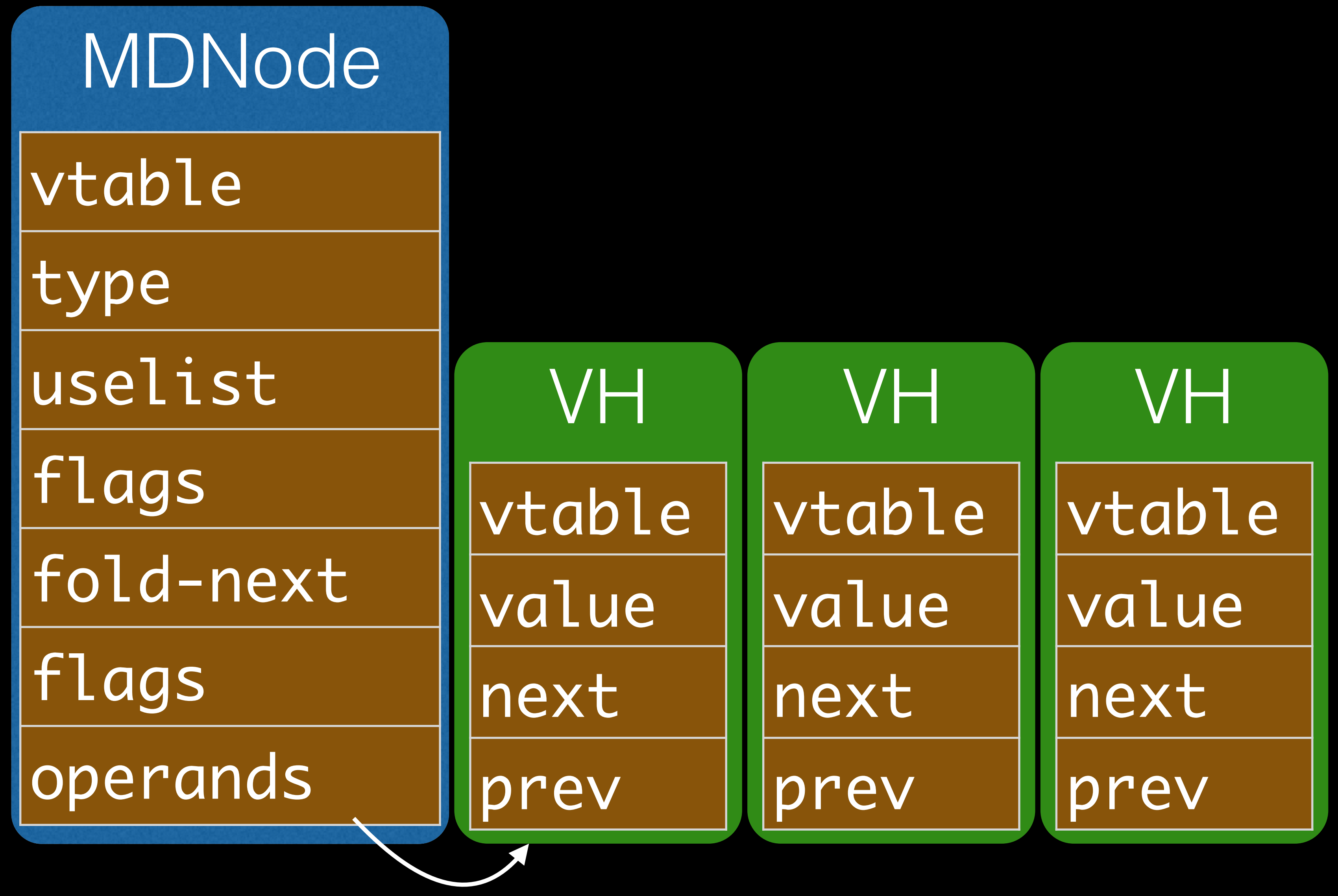
ValueHandles are second-class



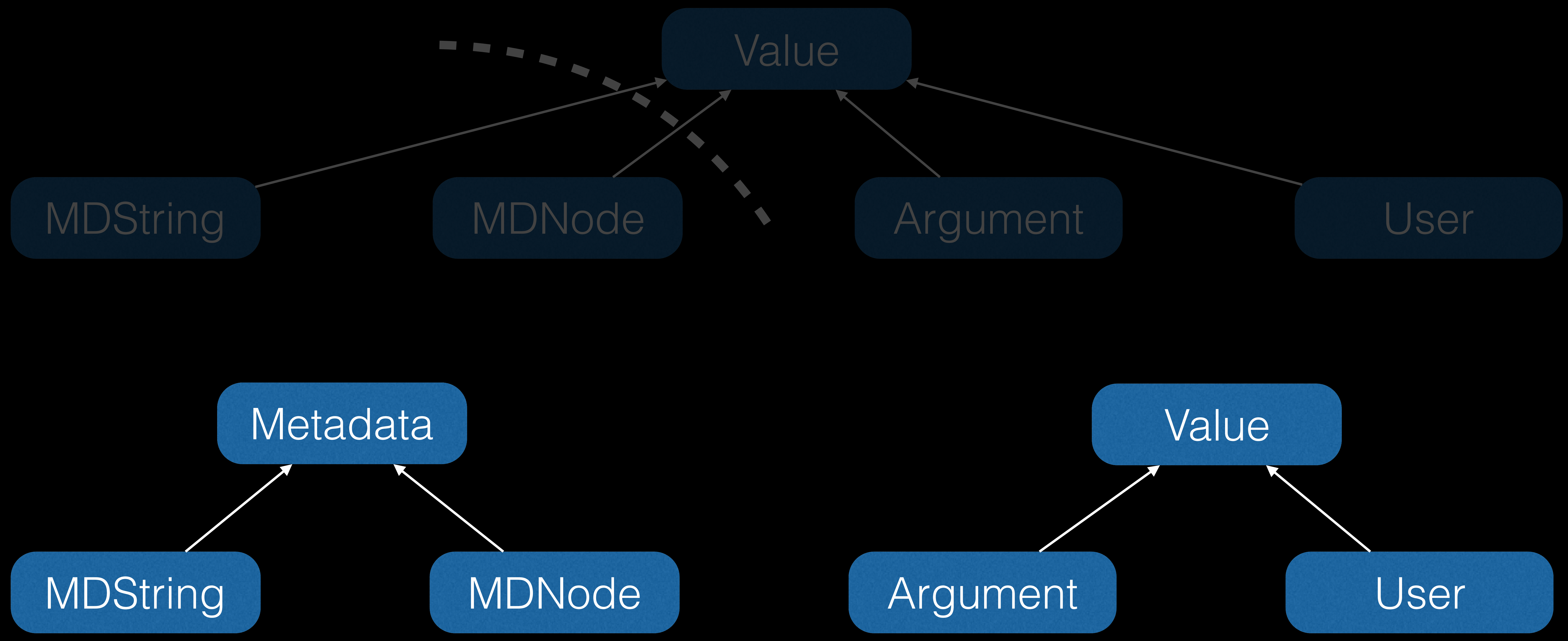
How did operands work?



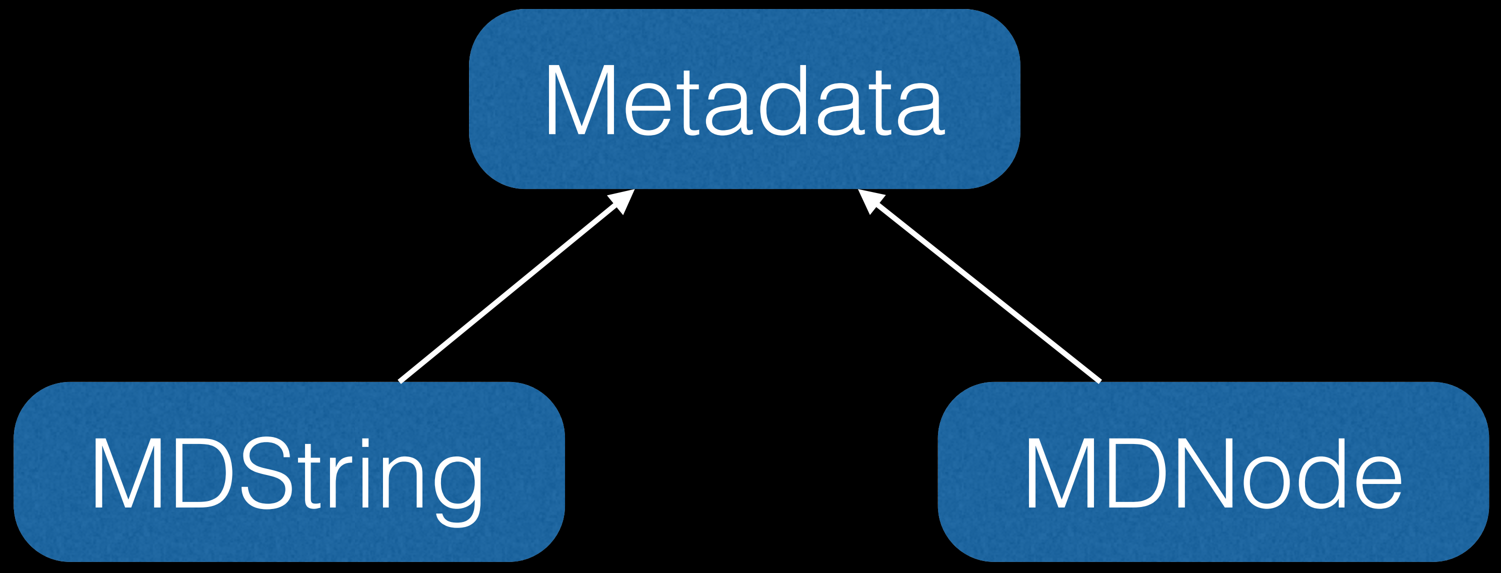
old MDNode operands were an array of ValueHandles



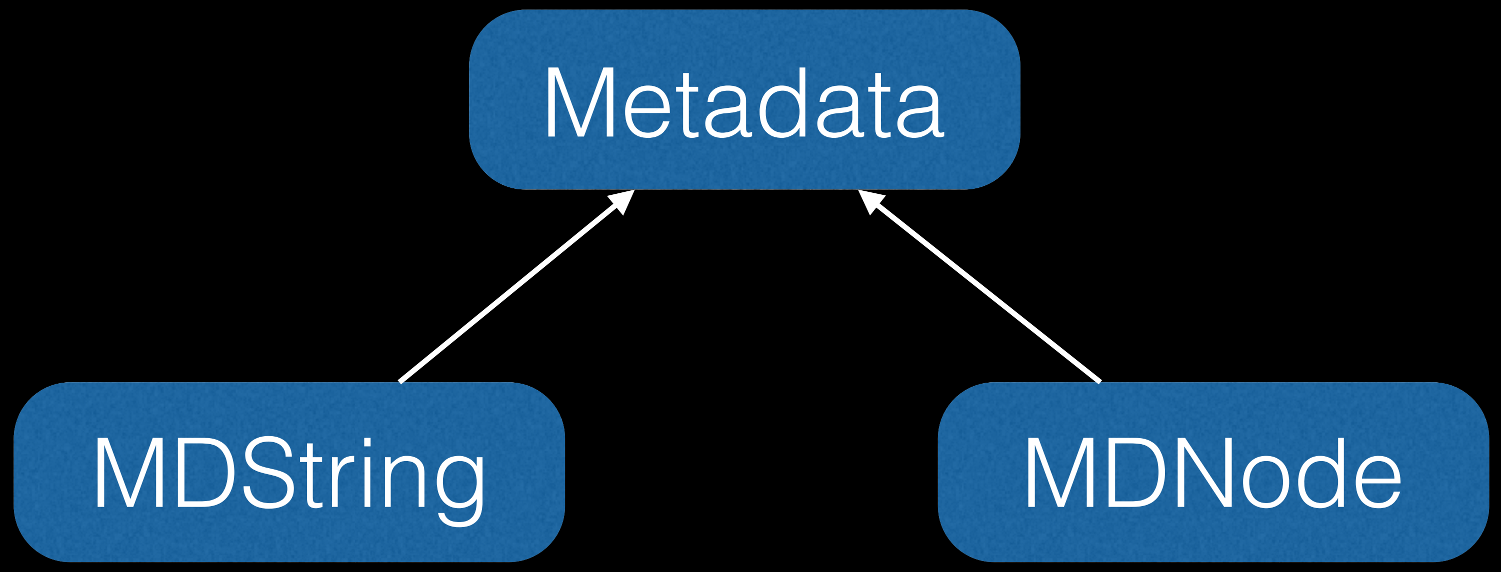
Separating Metadata from Value



Separating Metadata from Value

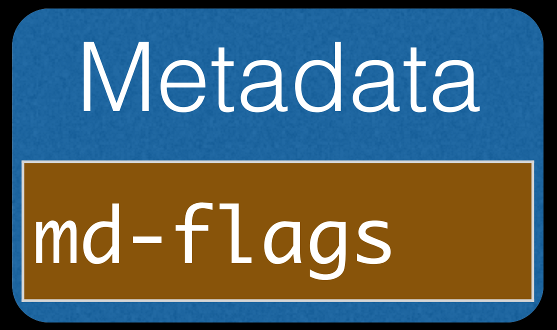


Metadata is lightweight

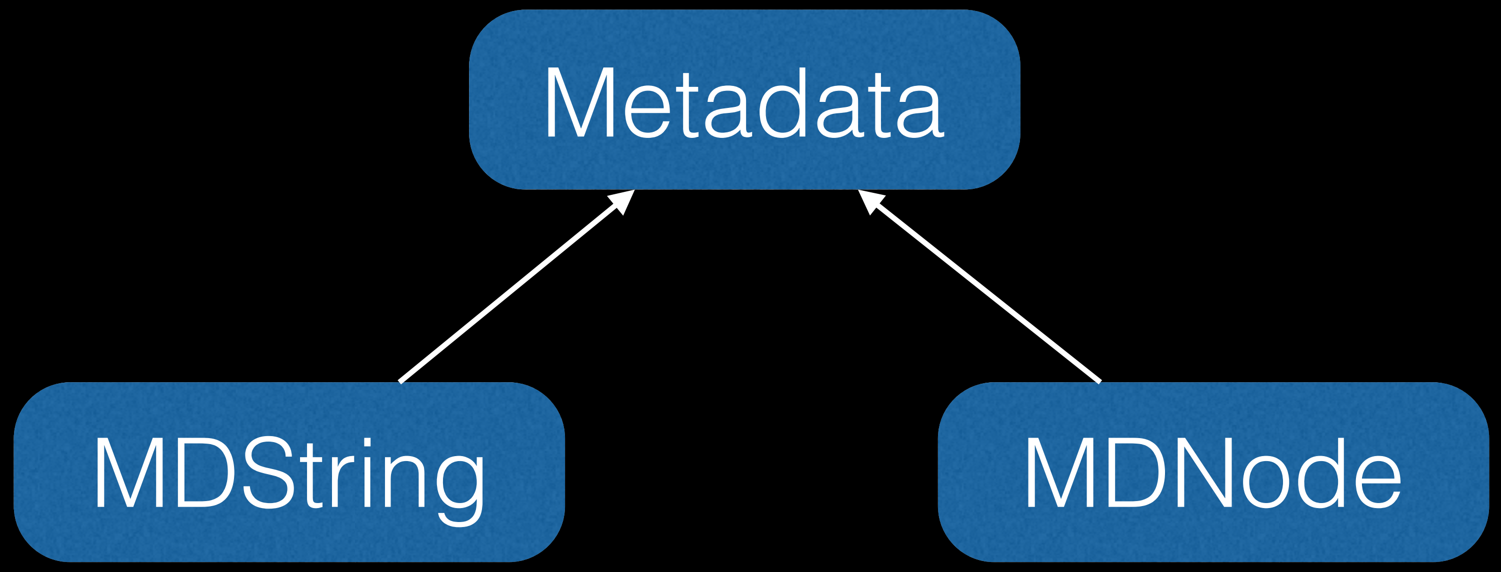


Metadata base class has size of 1 pointer

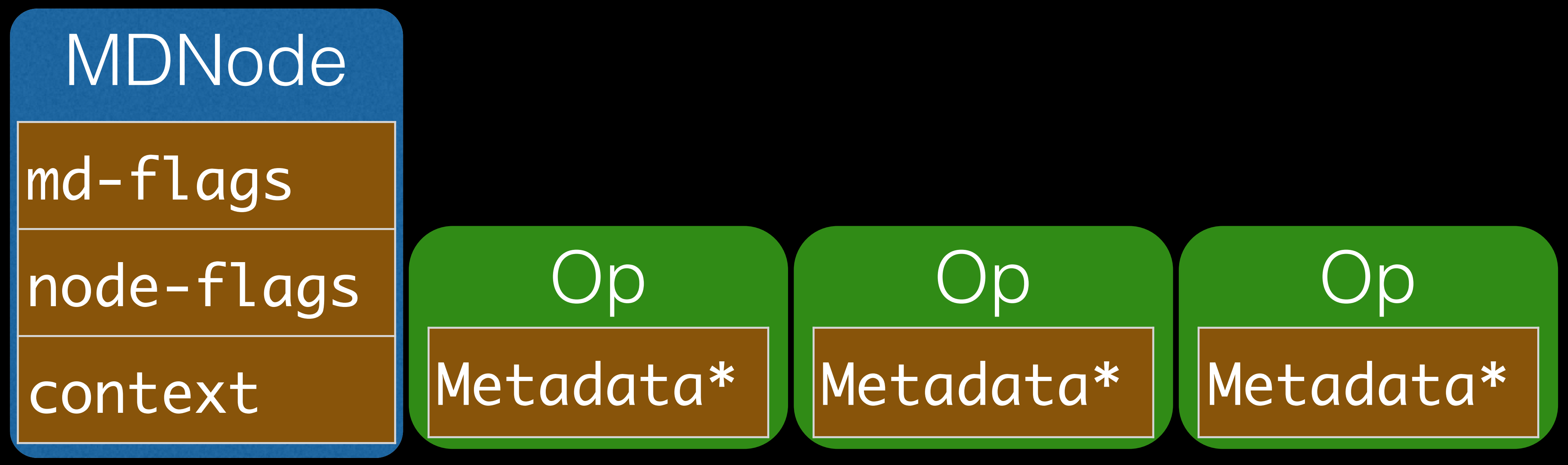
- no vtable
- no use-lists
- no Type pointer



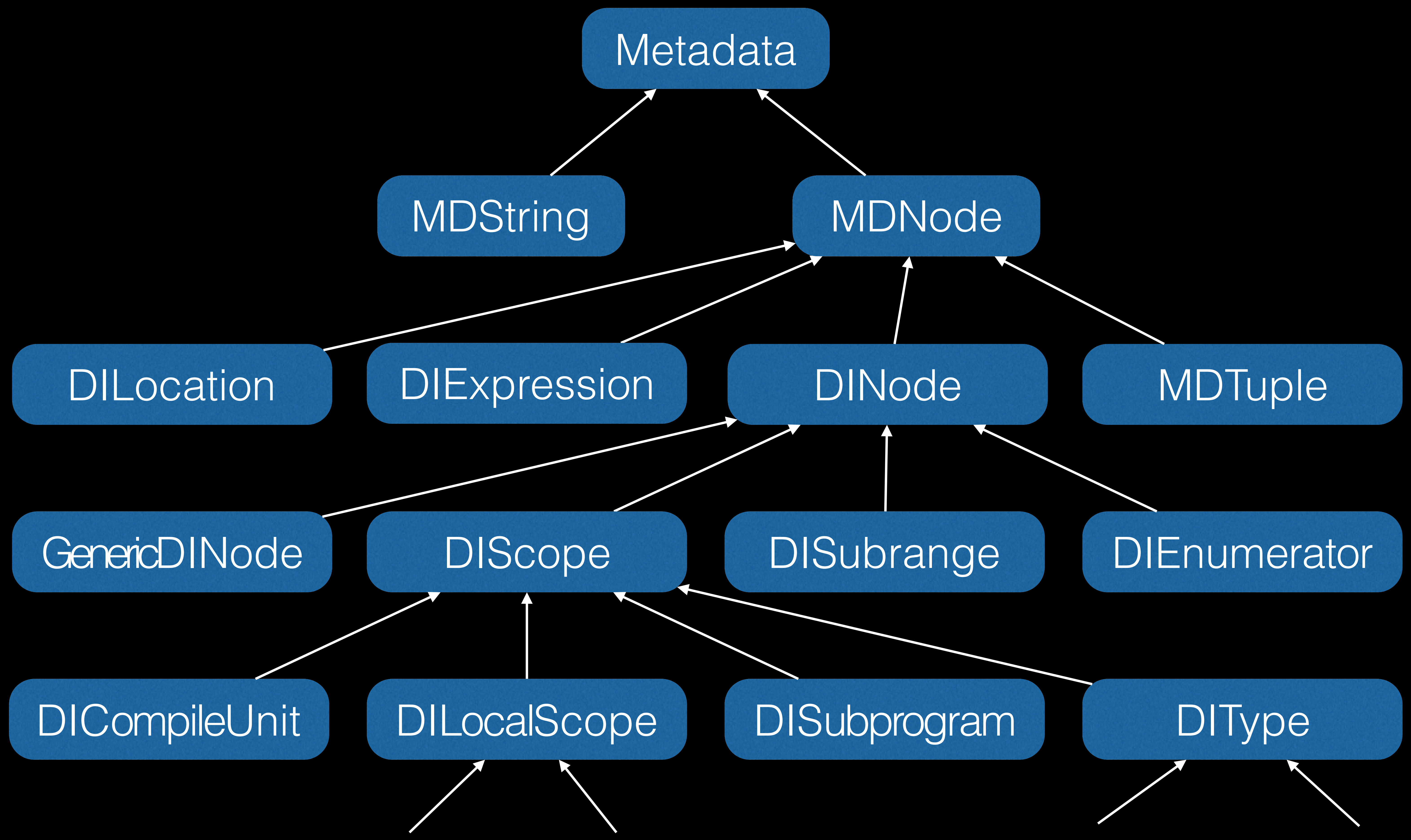
Metadata is lightweight



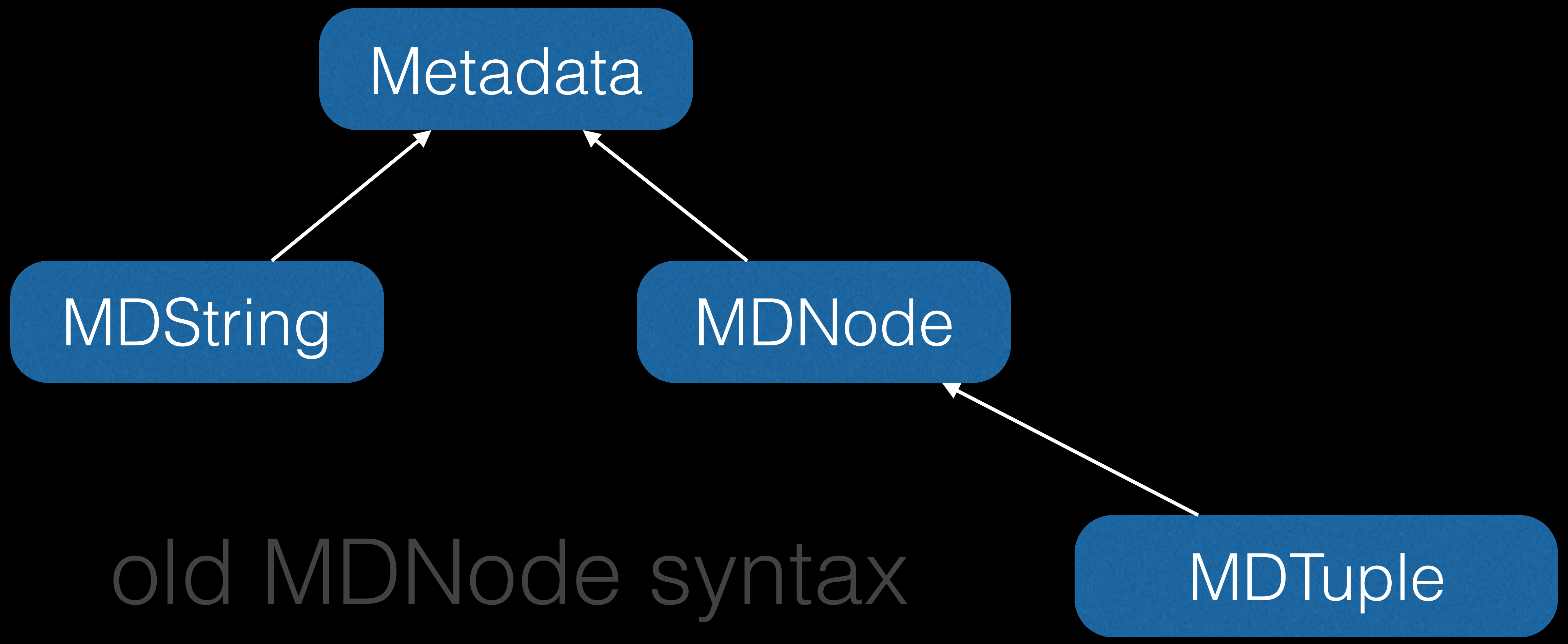
new MDNode operands are 4x smaller



Specialized MDNodes for debug info



MDTuple: generic MDNode



old MDNode syntax

```
!1 = metadata !{metadata !2, metadata !"string"}
```

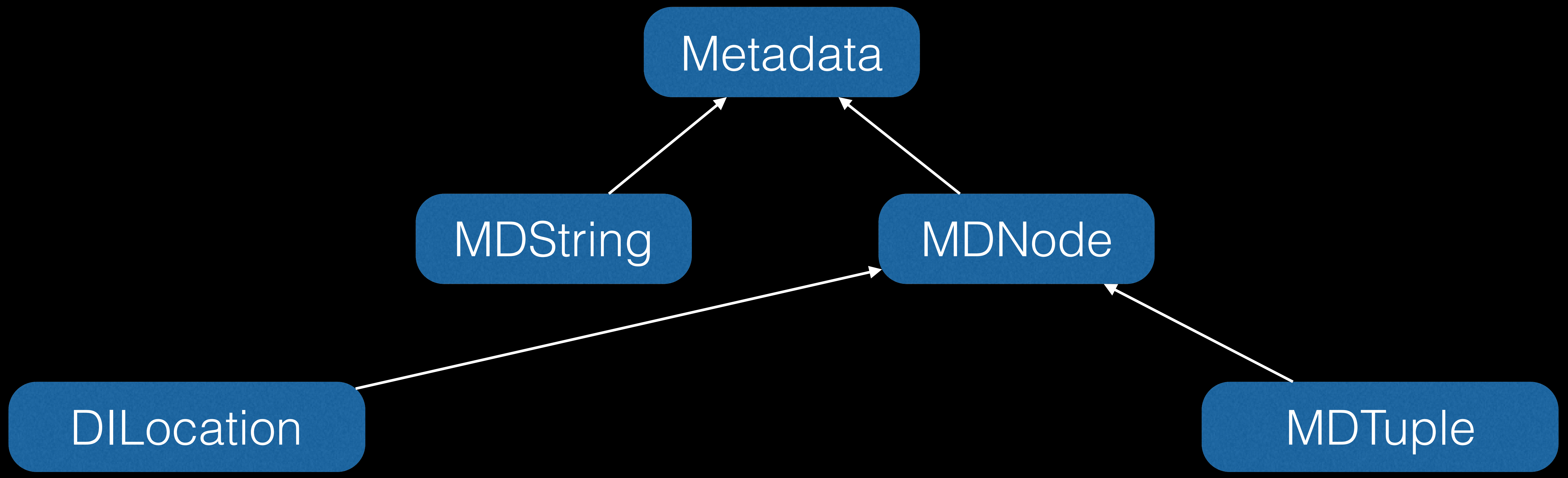
MDTuple syntax

```
!1 = !{!2, !"string"}
```

isa support

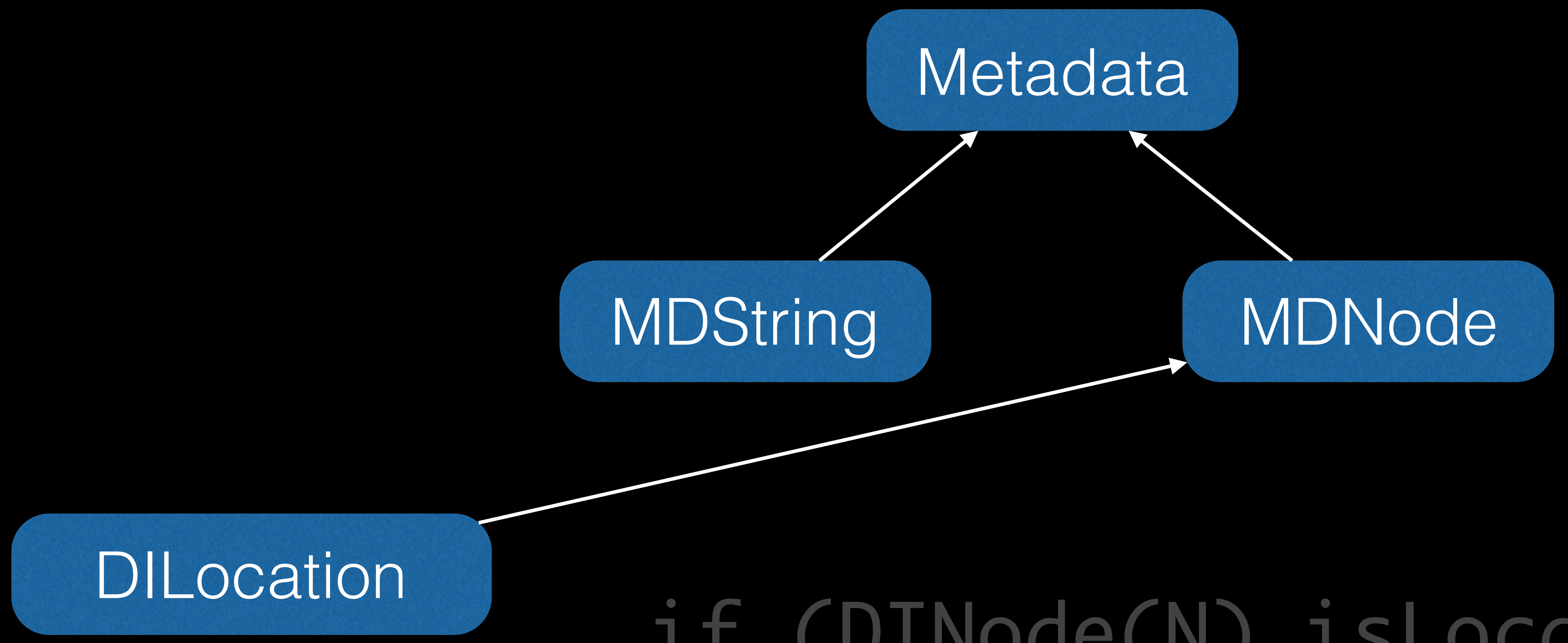
```
if (isa<MDTuple>(N)) { ... }
```

DILocation: syntax




```
!1 = metadata !{i32 30, i32 7, metadata !2, null}

!1 = !DILocation(line: 30, column: 7, scope: !2)
```

DILocation: **isa** support



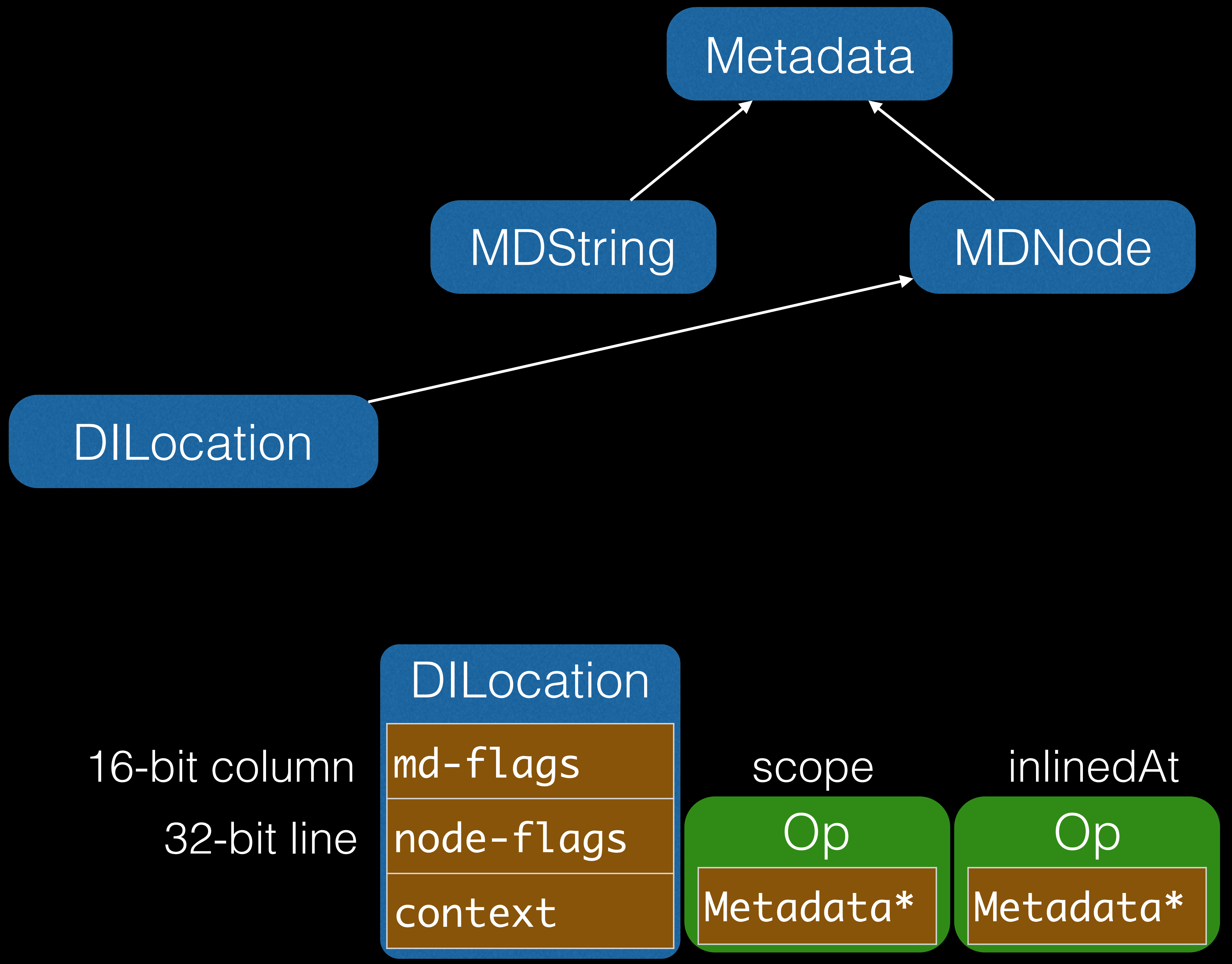

```
if (DINode(N).isLocation()) { ... }
```

isLocation():

```
if (auto *N = dyn_cast<MDNode>(V))
  if ((N->getNumOperands() == 3 ||
       N->getNumOperands() == 4) &&
      isa<ConstantInt>(N->getOperand(0) &&
      isa<ConstantInt>(N->getOperand(1) &&
      DINode(N).isScope(N->getOperand(2)) { ... }
```

```
if (isa<DILocation>(N)) { ... }
```

DILocation: memory footprint



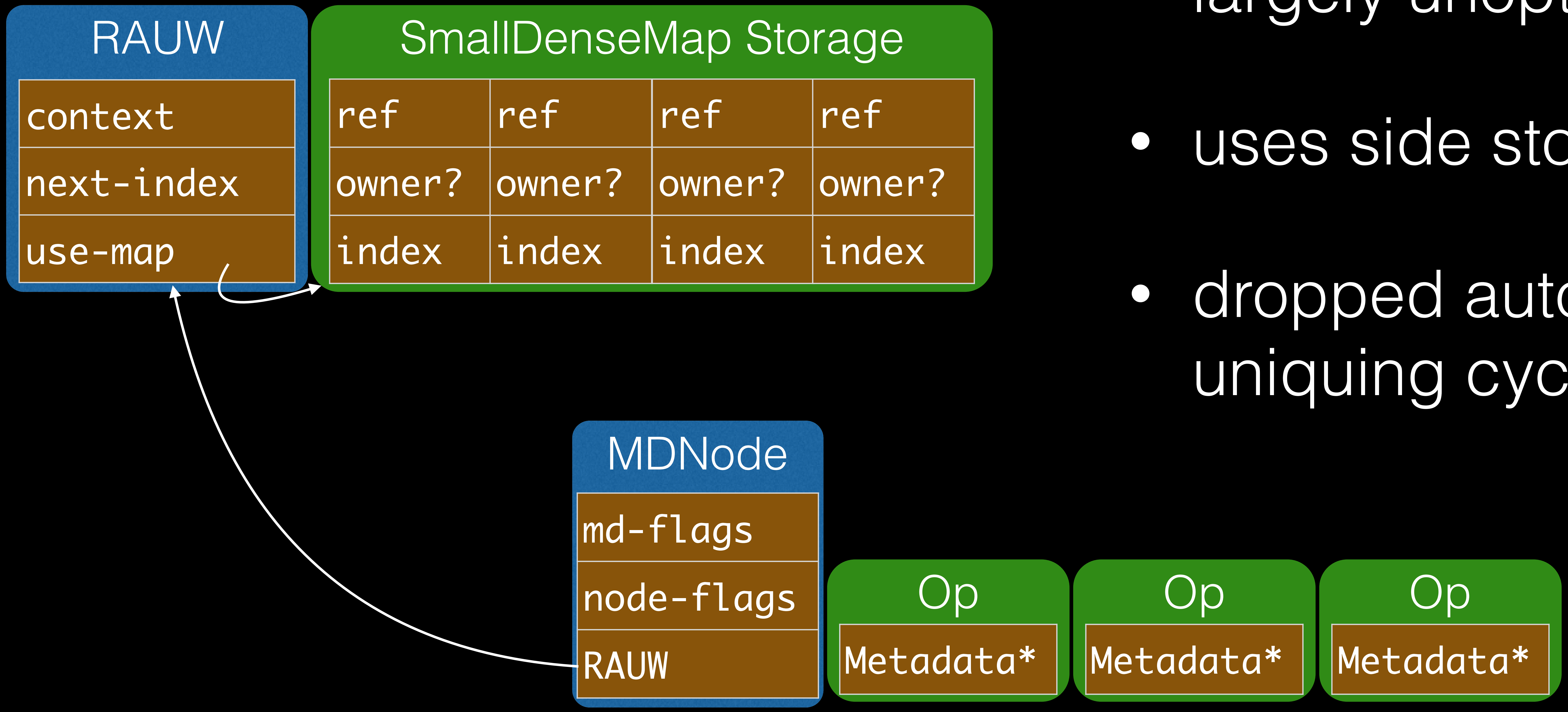
What about other Metadata graphs?

- we should have more primitives for generic Metadata
  - MDInt and MDFloat: skip ConstantInt and ConstantFloat
  - vectors, dictionaries and lists (when tuples don't fit)
- specialized nodes: syntax, **isa** support, and memory footprint
  - what makes a graph important and/or stable enough?
  - can we enable it for out-of-tree nodes?

Constructing Metadata graphs

- frontends (DIBuilder), bitcode deserialization, and lib/Linker build metadata graphs
- need temporary nodes for forward references
- need use-lists (and RAUW support) to replace temporary nodes
  - Metadata use-lists are second-class
  - how can we limit exposure to use-lists?

Temporary storage for explicit use-lists



- largely unoptimized
- uses side storage
- dropped automatically, except uniquing cycles

Constructing a graph

!0 = !{!1}

!1 = !{!2}

!2 = !{}

how can we build this graph?

Constructing a graph, top-down

1'

!0 = !{!1}
!1 = !{!2}
!2 = !{}

create temporary node for !1

Constructing a graph, top-down

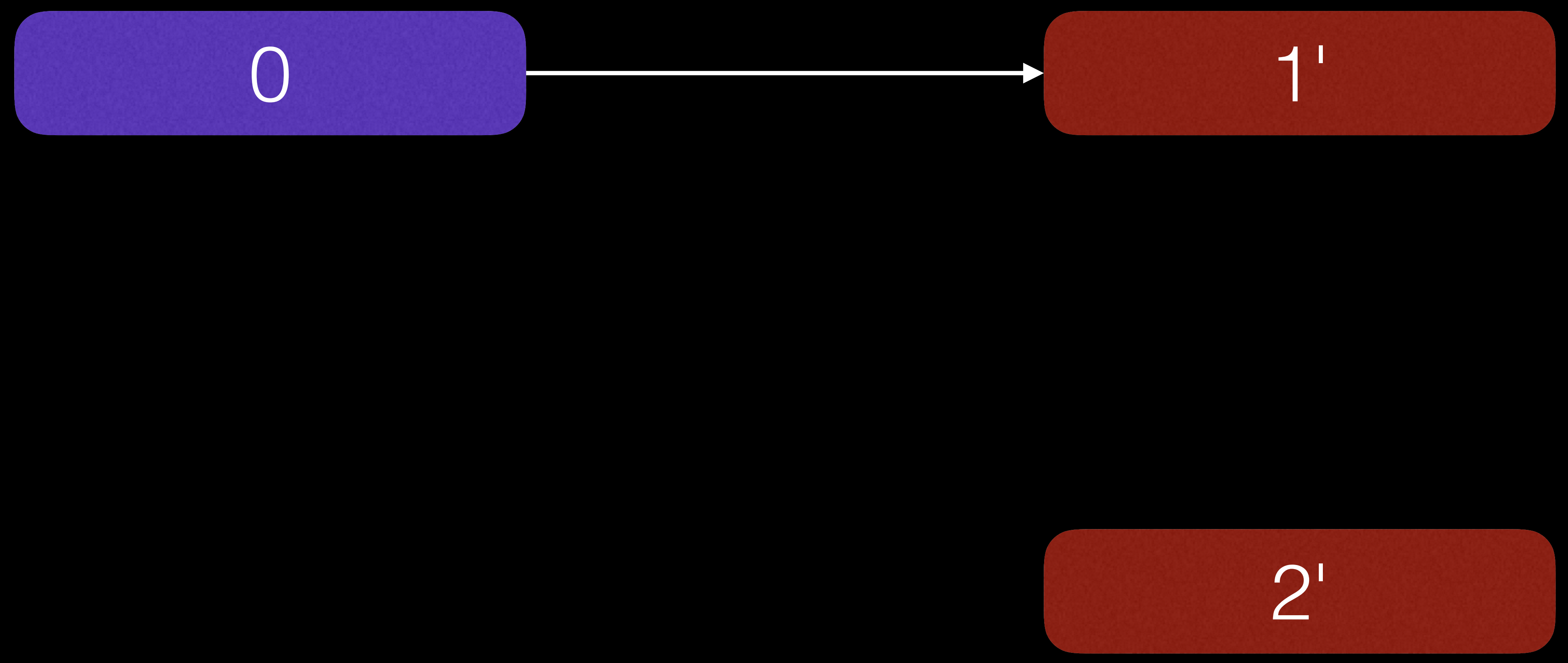
!0 = !{!1}

!1 = !{!2}

!2 = !{}

create (unresolved) node for !0

Constructing a graph, top-down

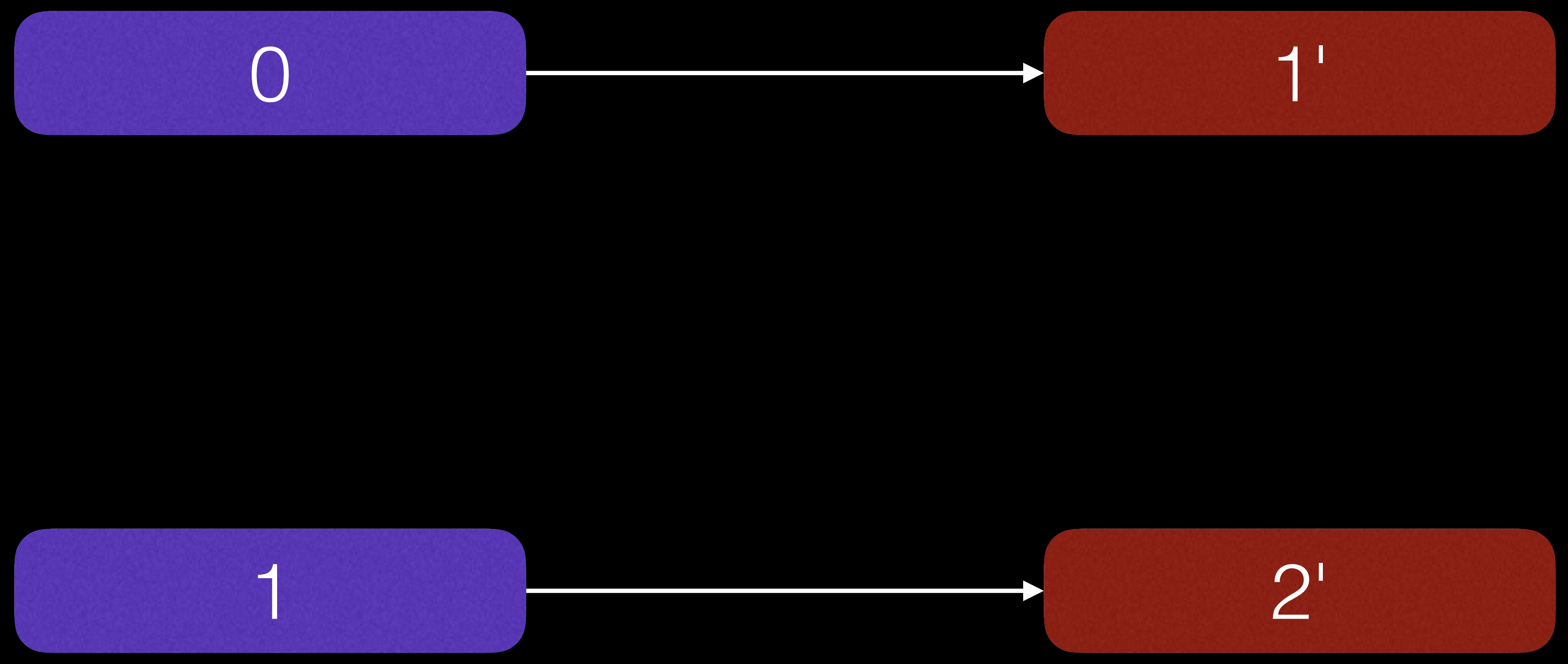


!0 = !{!1}
!1 = !{!2}
!2 = !{}

create temporary node for !2

Constructing a graph, top-down

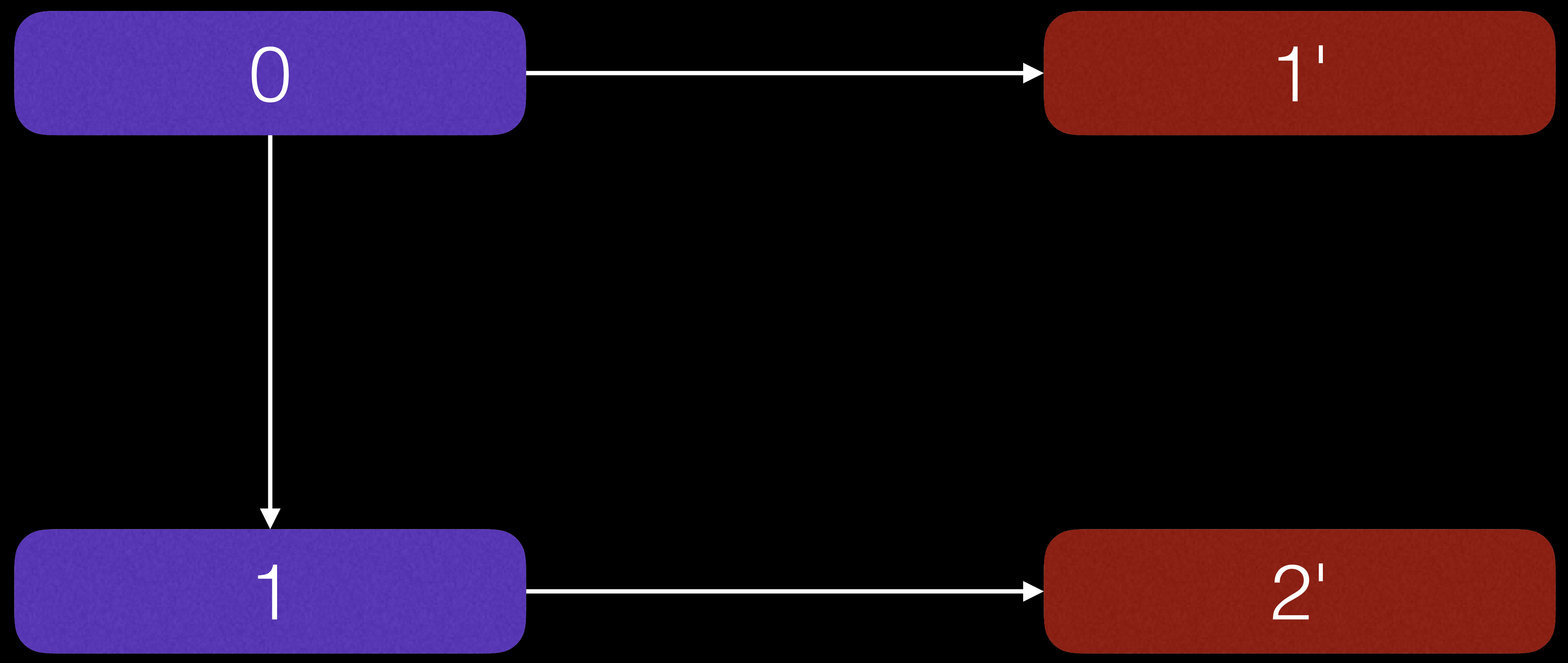
!0 = !{!1}
!1 = !{!2}
!2 = !{}



create (unresolved) node for !1

Constructing a graph, top-down

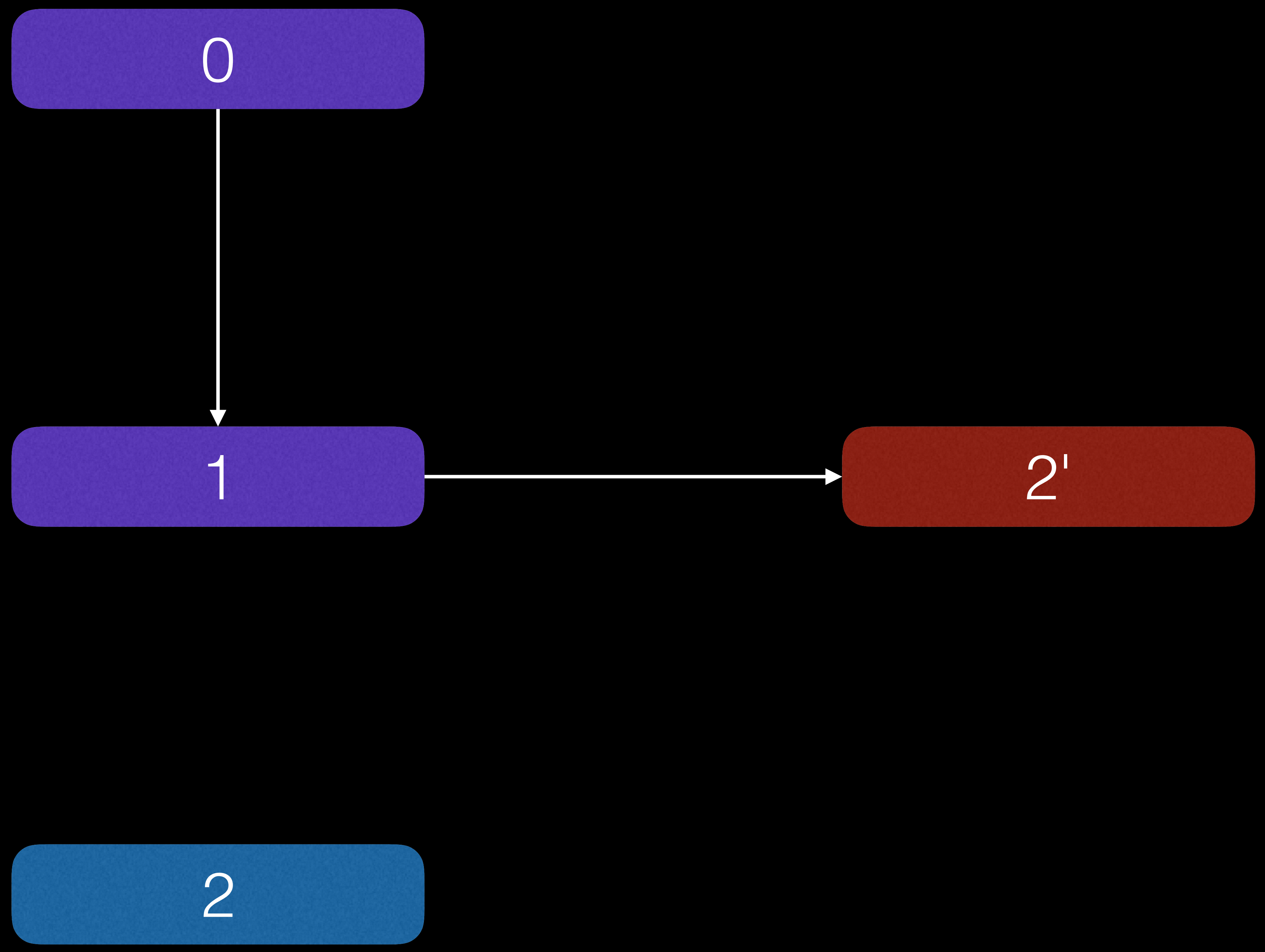
!0 = !{!1}
!1 = !{!2}
!2 = !{}



replace temporary node for !1 with real node

Constructing a graph, top-down

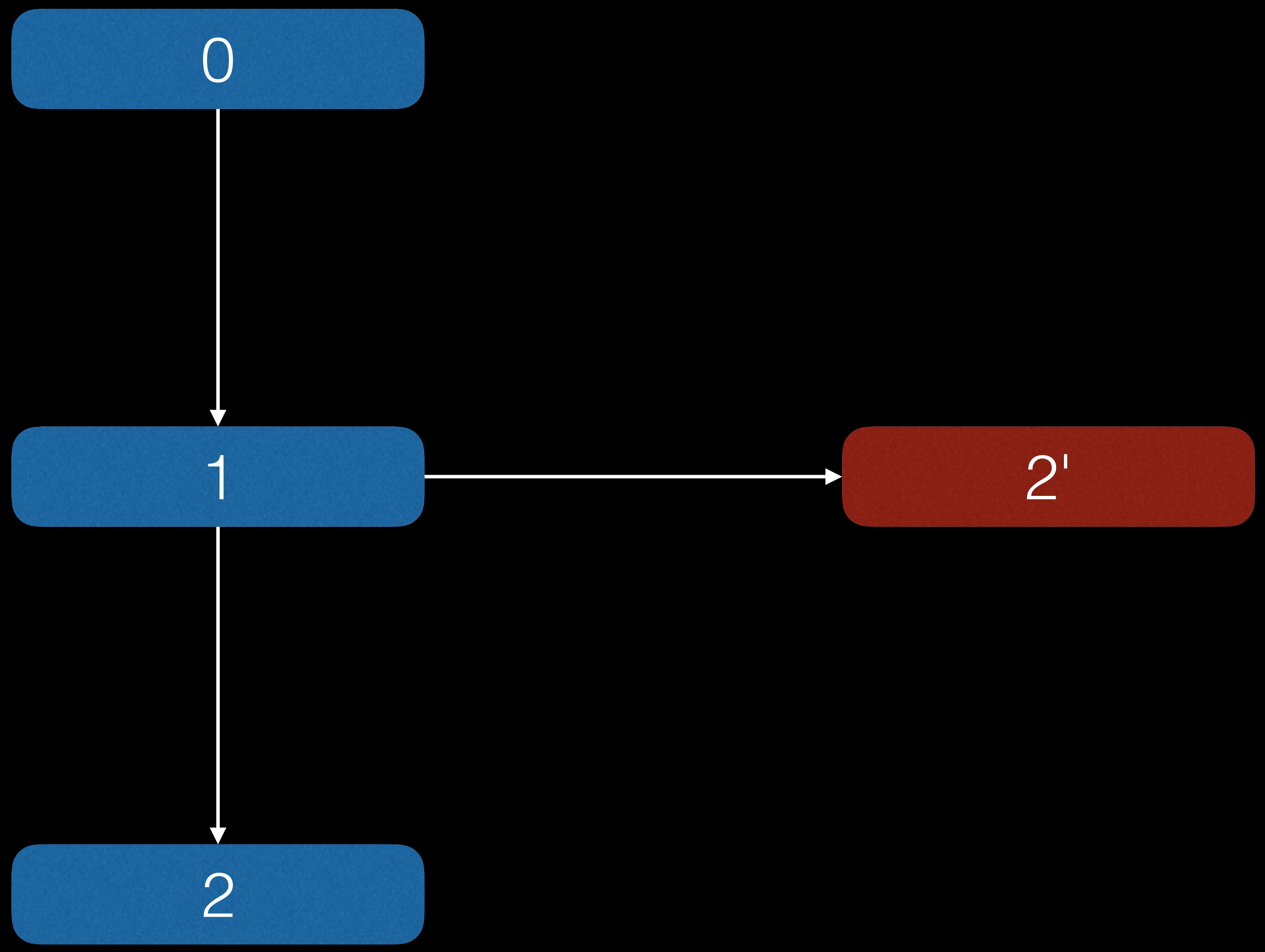
!0 = !{!1}
!1 = !{!2}
!2 = !{}



create node for !2

Constructing a graph, top-down

!0 = !{!1}
!1 = !{!2}
!2 = !{}



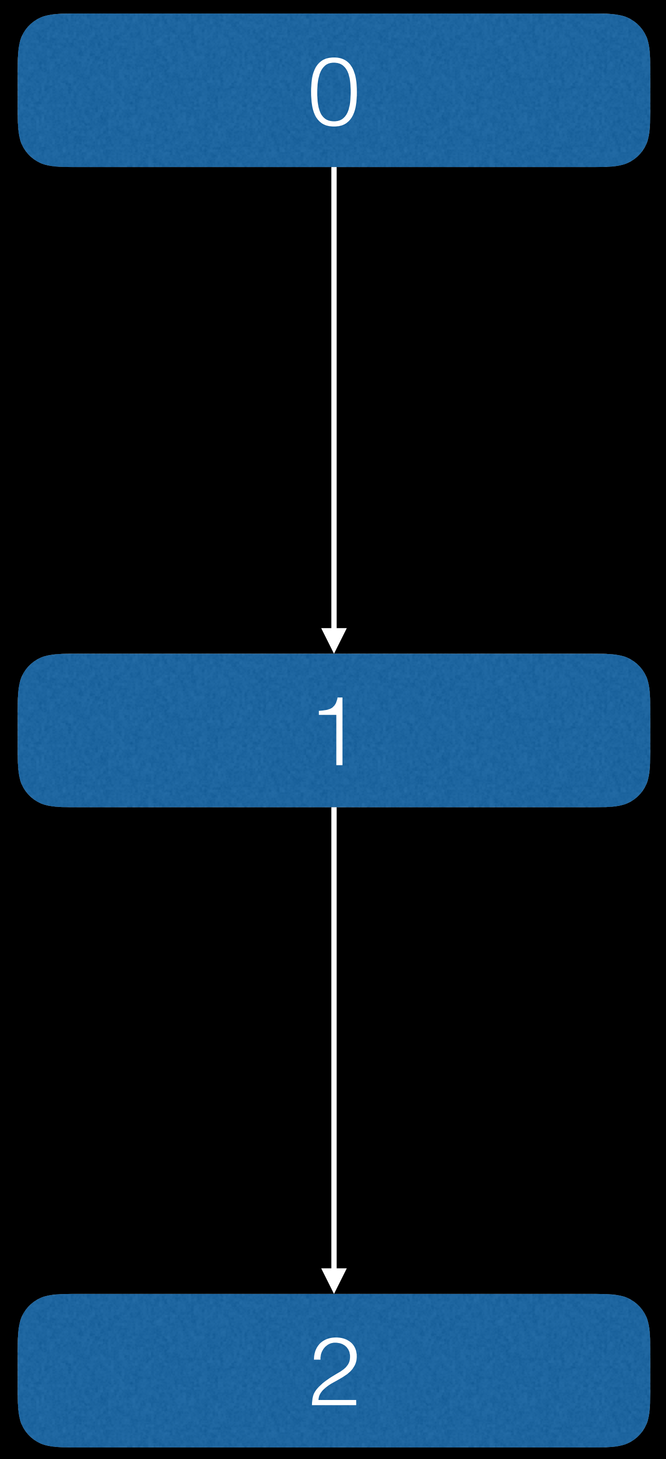
replace temporary node for !2 with real node, resolving !1 and !0

Constructing a graph, top-down

!0 = !{!1}

!1 = !{!2}

!2 = !{}



that was a lot of RAUW and malloc traffic...

Constructing a graph, bottom-up

```
!0 = !{!1}
!1 = !{!2}
!2 = !{}
```

avoid malloc traffic and RAUW by reversing the order

Constructing a graph, bottom-up

!0 = !{!1}

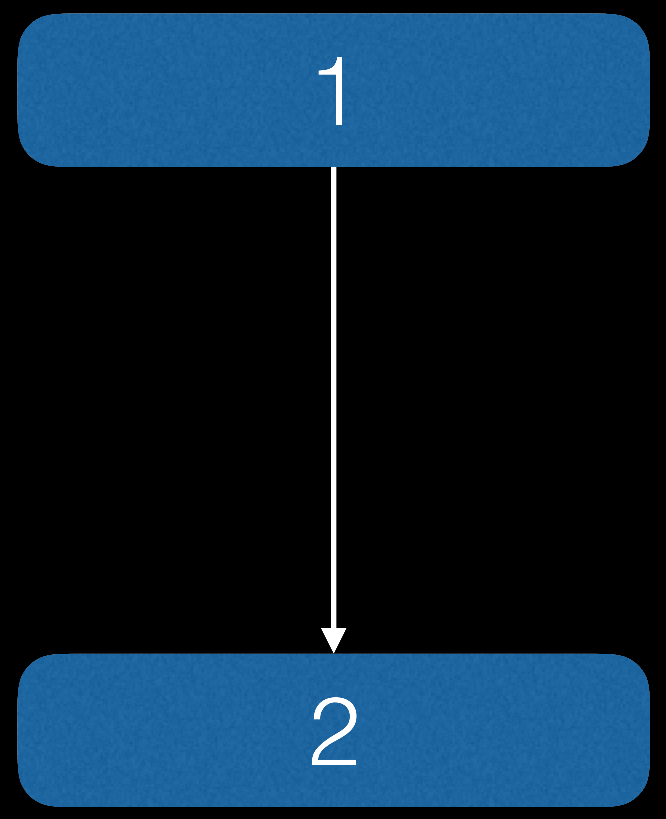
!1 = !{!2}

!2 = !{}

create node for !2

Constructing a graph, bottom-up

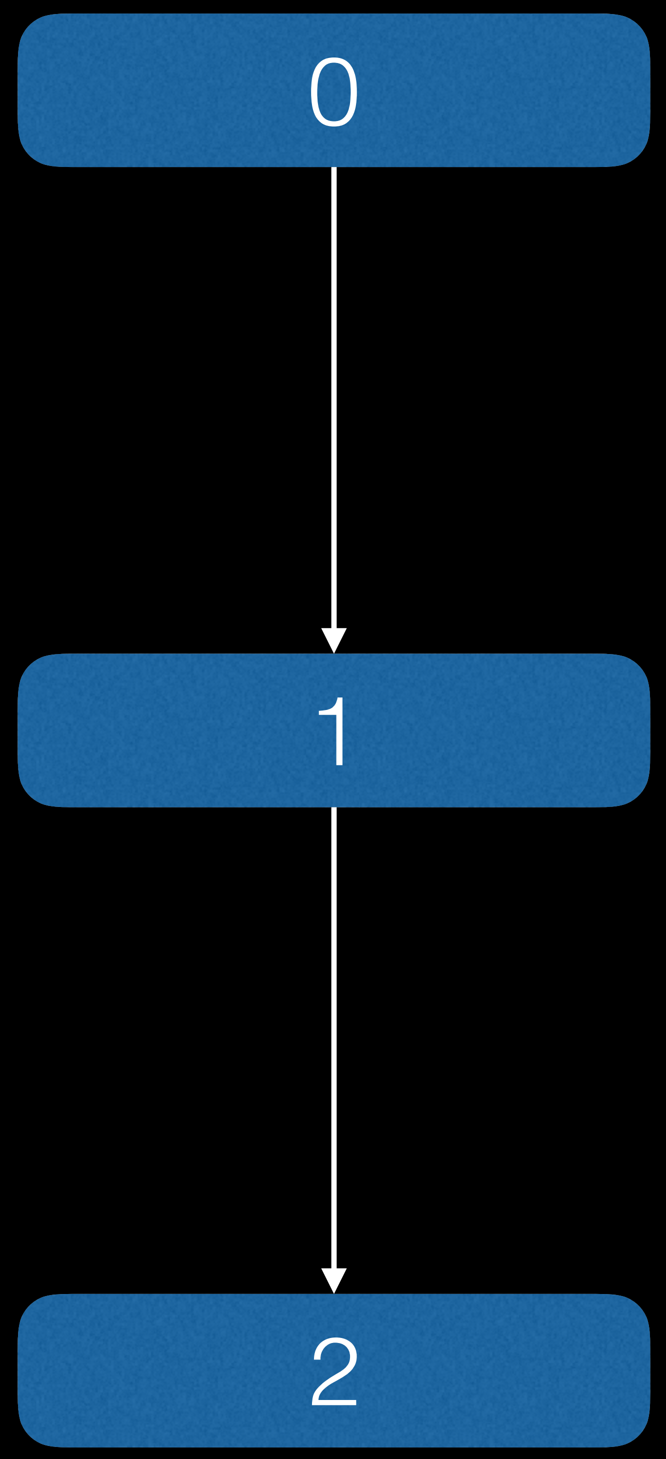
!0 = !{!1}
!1 = !{!2}
!2 = !{}



create node for !1

Constructing a graph, bottom-up

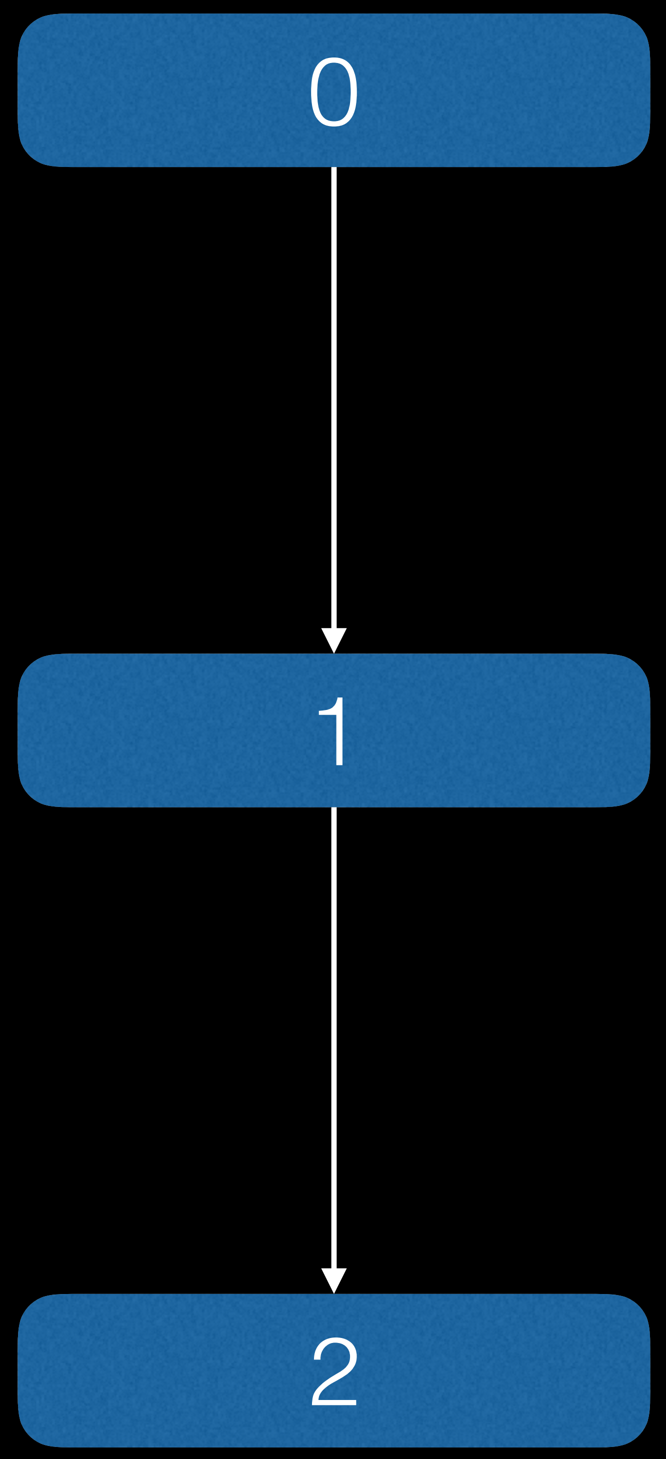
!0 = !{!1}
!1 = !{!2}
!2 = !{}



create node for !0

Constructing a graph, bottom-up

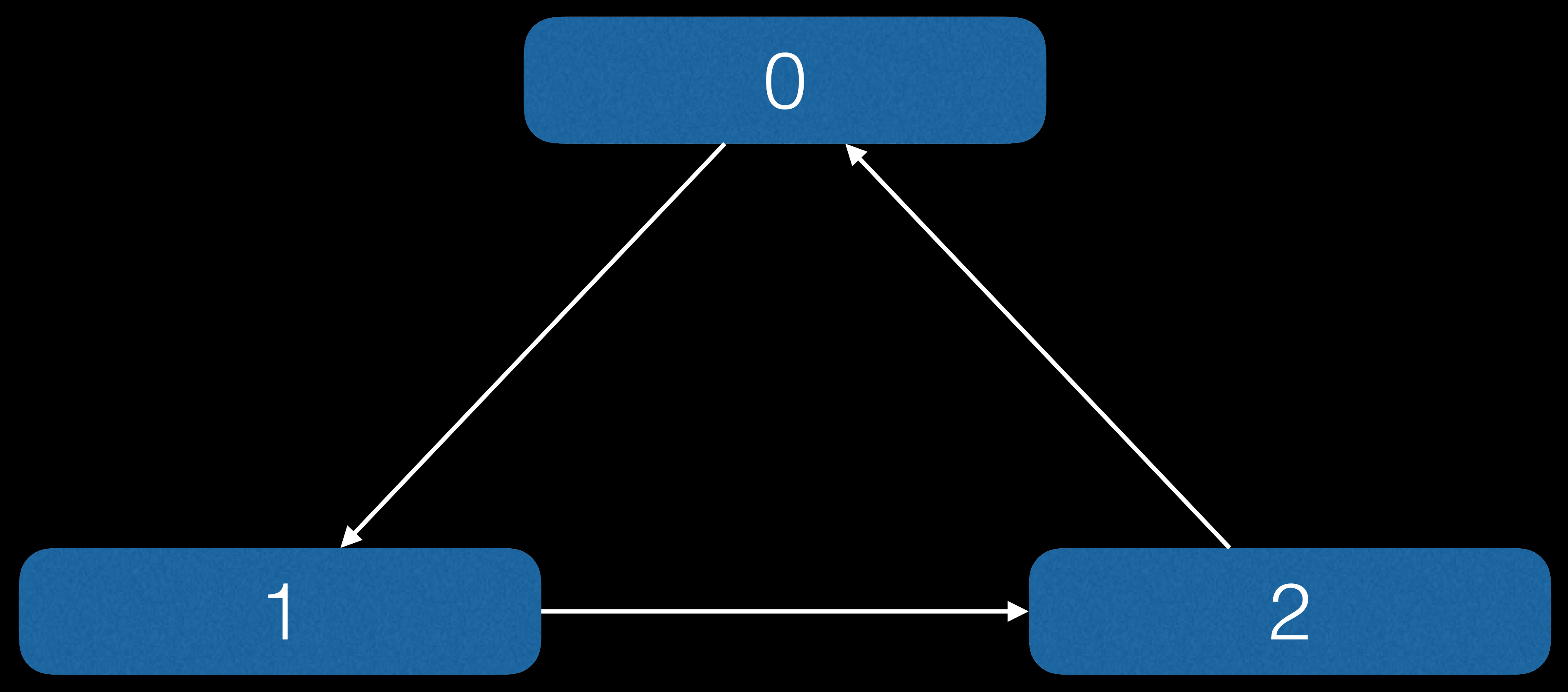
!0 = !{!1}
!1 = !{!2}
!2 = !{}



no extra malloc traffic; no RAUW

Constructing a cycle of uniqued nodes

!0 = !{!1}
!1 = !{!2}
!2 = !{!0}



building a cycle of uniqued nodes **requires** temporary nodes

Not every node should be uniqued

- graphs intentionally defeat uniquing when they want distinct nodes
    - !alias.scopes need distinct root nodes
    - DILexicalBlocks lack naturally discriminating operands
- cycles of uniqued nodes need forward references and RAUW
- cycles of uniqued nodes "look" distinct
    - we don't solve graph isomorphism

distinct nodes are more efficient

- **distinct** nodes are not uniqued

```
!1 = distinct !{}
!2 = distinct !{}
```

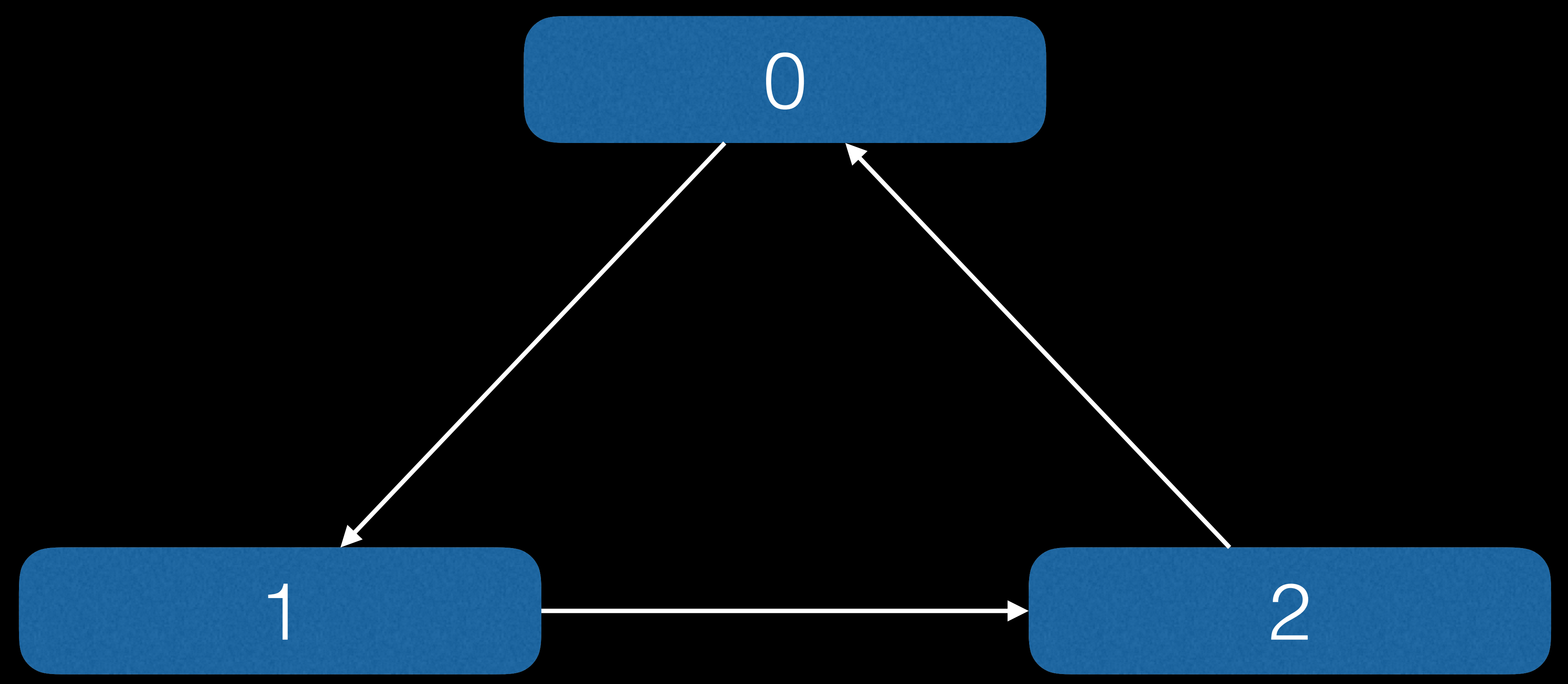
  - note: self-references are automatically **distinct**

```
!1 = !{!1}    →    !1 = distinct !{!1}
```

- no re-uniquing penalty when operands change
- never require use-lists (or RAUW support)

Constructing cyclic graphs efficiently

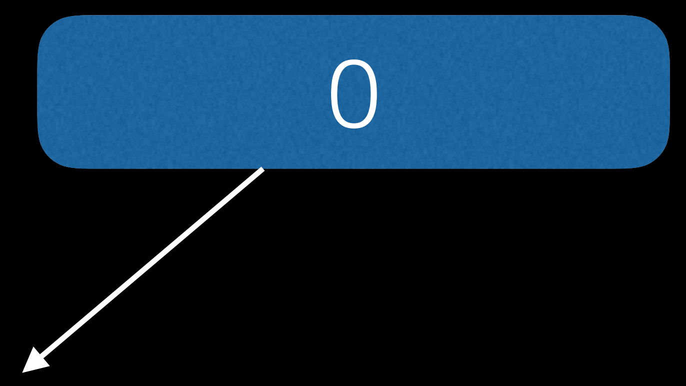
!0 = distinct !{!1 }
!1 = !{!2}
!2 = !{!0}



we can do better with **distinct** nodes

Constructing cyclic graphs efficiently

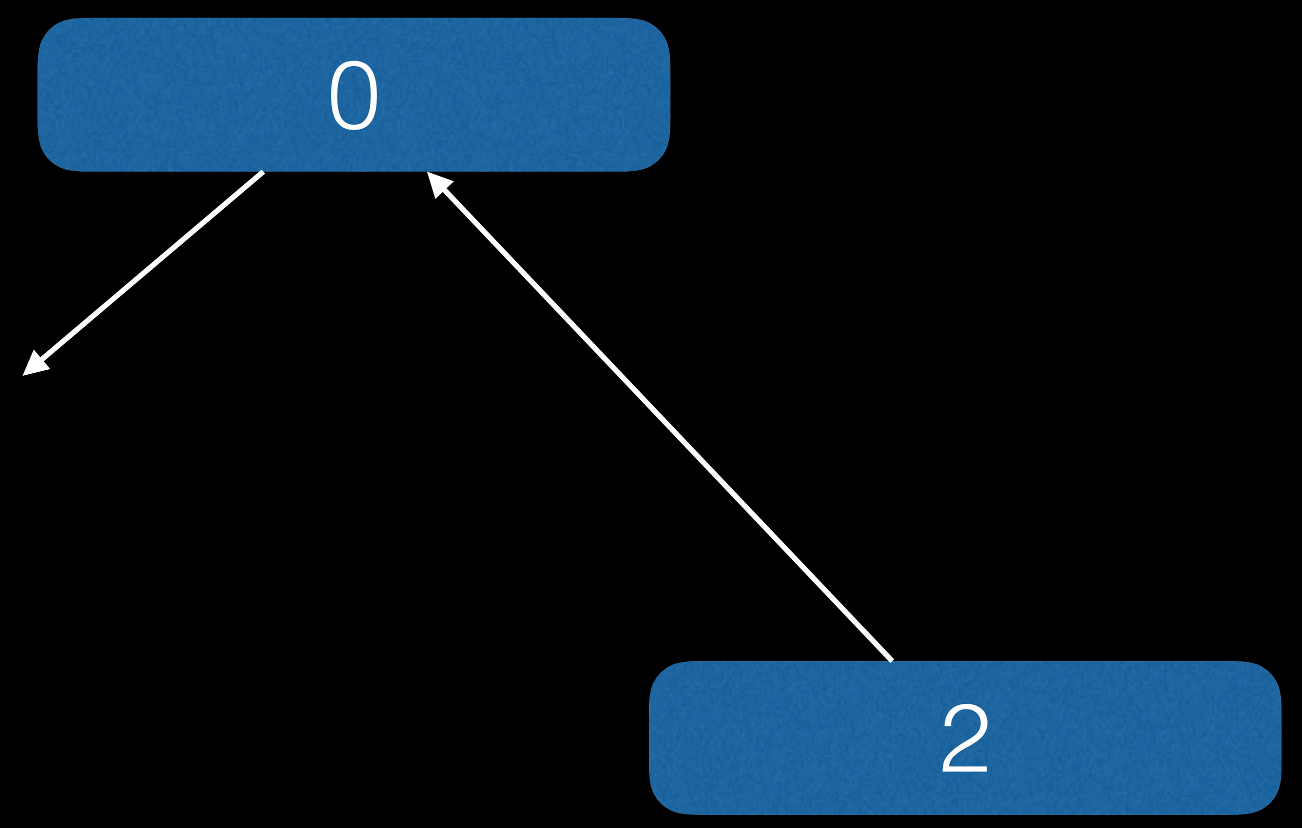
!0 = distinct !{!1}
!1 = !{!2}
!2 = !{!0}



create node for !0, with a dangling operand

Constructing cyclic graphs efficiently

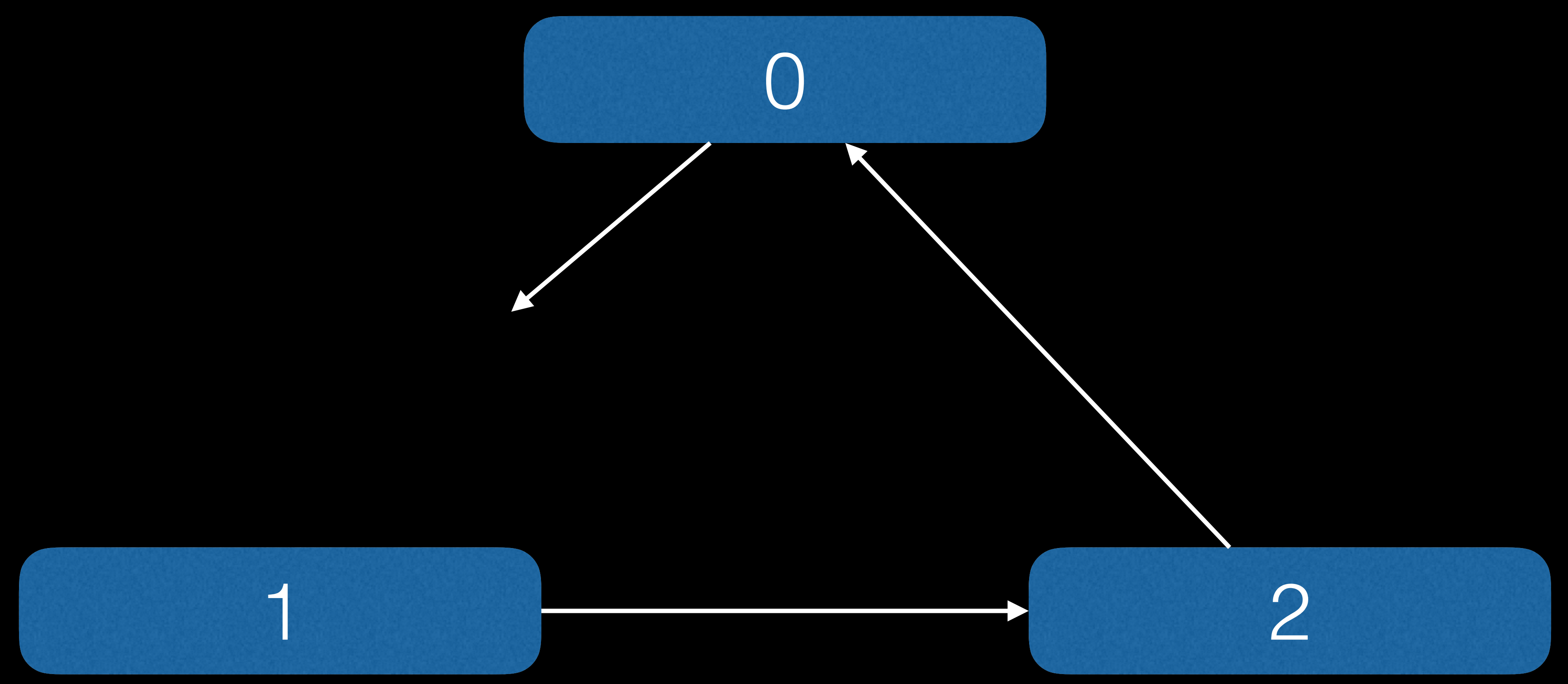
!0 = distinct !{!1}
!1 = !{!2}
!2 = !{!0}



create node for !2

Constructing cyclic graphs efficiently

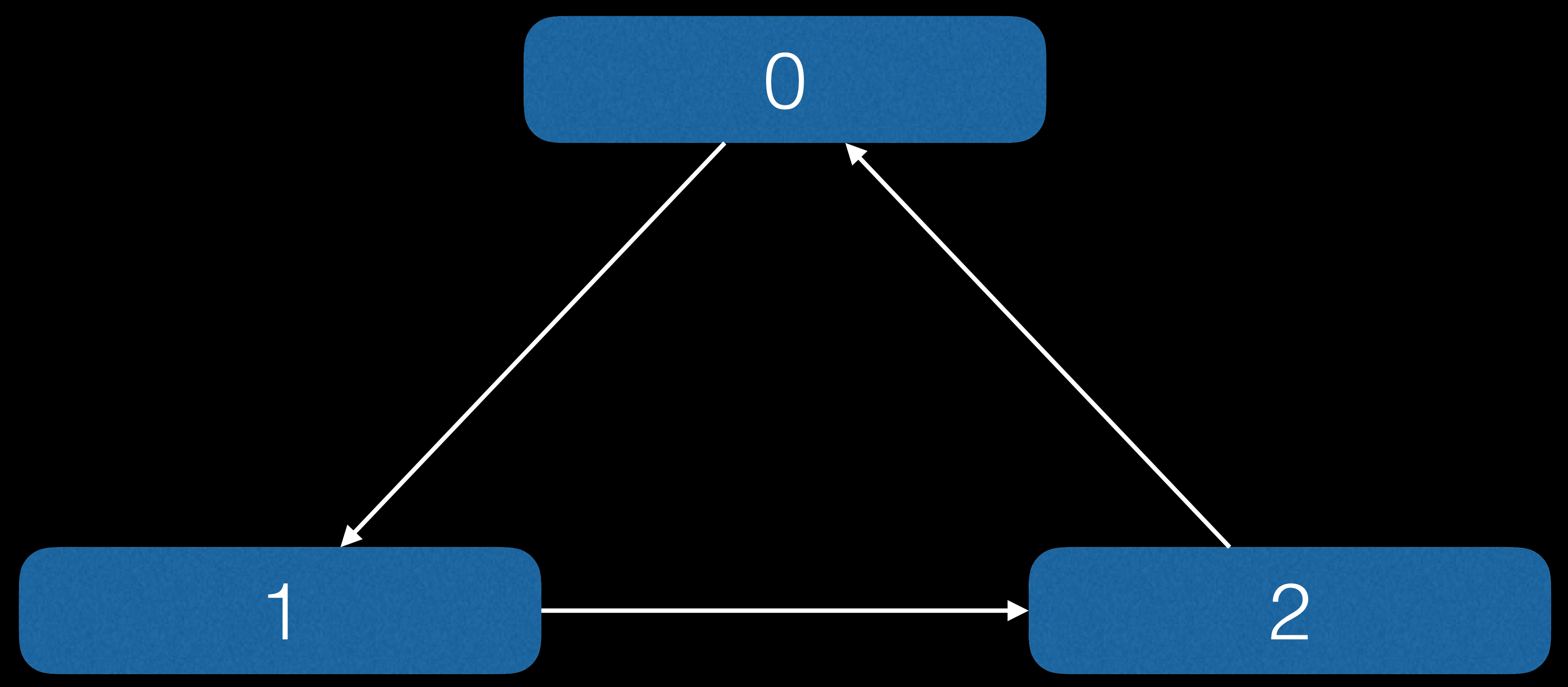
!0 = distinct !{!1 }
!1 = !{!2}
!2 = !{!0}



create node for !1

Constructing cyclic graphs efficiently

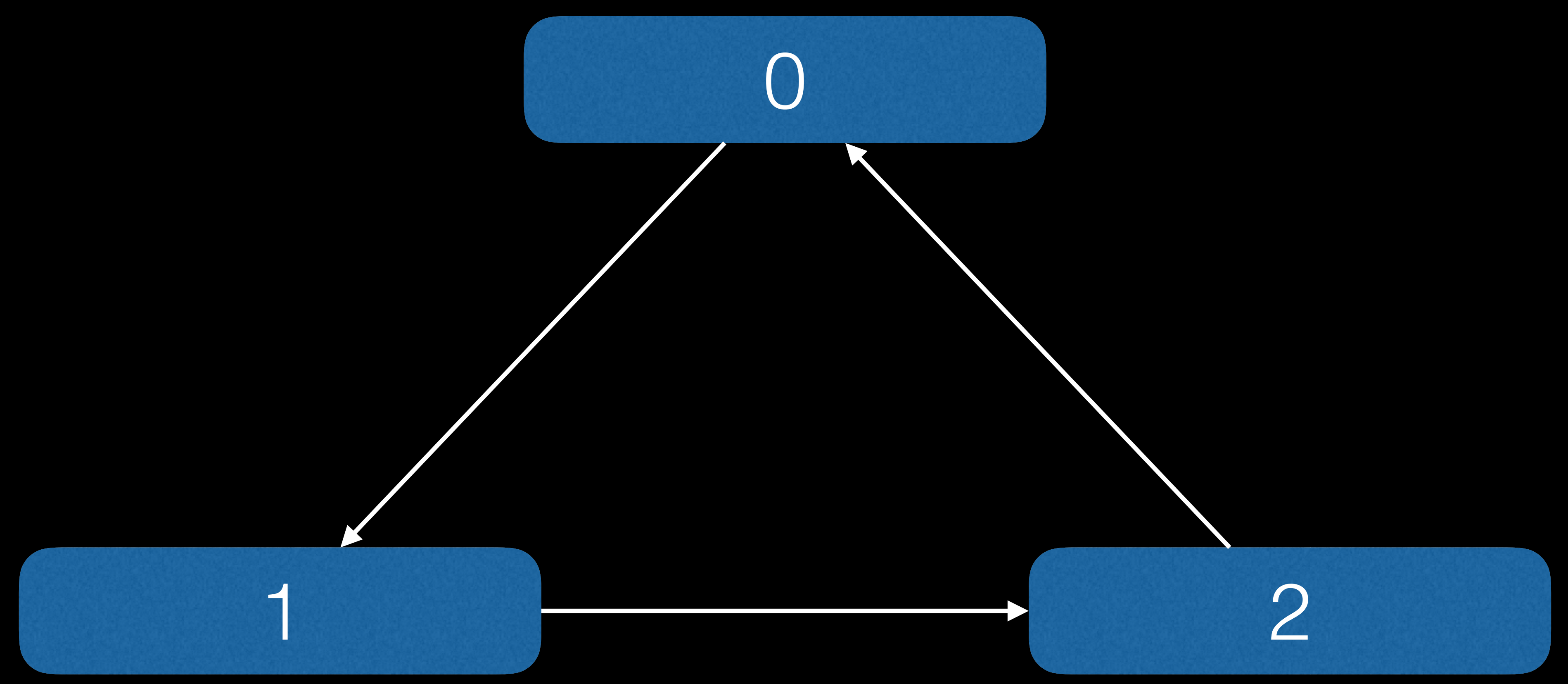
!0 = distinct !{!1 }
!1 = !{!2}
!2 = !{!0}



patch operand(s) for !0

Constructing cyclic graphs efficiently

!0 = distinct !{!1}
!1 = !{!2}
!2 = !{!0}



- careful scheduling avoids malloc traffic and RAUW
- partial support in lib/Linker; not done in BitcodeReader (yet)

Grab bag: other major LTO optimizations

- Metadata lazy-loaded (in bulk); new LTO API to expose it
- avoided lib/Linker quadratic memory leak into LLVMContext from globals with appending linkage
- debug info requires fewer MCSymbols (and they're cheaper)
- Value has dropped a couple of pointers

What progress have we made?

runtime and peak memory usage of ld, when linking executables from 3.6 (r240577) source tree

compiler version	small (verify-uselistorder)		medium (llvm-lto)		large (clang)	
3.5 (r232544)	48s	2.27GB	10m 35s	22.8GB	25m 41s	75.6GB
3.6 (r240577)	38s	1.40GB	8m 32s	15.1GB	19m 45s	35.9GB
3.7 (r247539)	35s	0.79GB	7m 52s	9.15GB	18m 10s	19.3GB
ToT (r250621)	34s	0.73GB	7m 37s	8.11GB	16m 23s	17.2GB
3.5 vs. ToT	1.4x	3.1x	1.4x	2.8x	1.6x	4.4x

self-hosted clang/libLTO, using ld64-253.2 from Xcode 7 on a 2013 Mac Pro with 32GB RAM

What's left in LLVM?

- use more **distinct** nodes; take more advantage of them
- richer syntax for scoped debug info nodes
- fine-grained lazy-loading of debug info metadata
  - debug info graphs need to be sliceable (link only what's used)
- MC-layer diet v2 (I'm looking at **you**, MCRelaxableFragment)
- leave debug info types out of LTO!

Debug Information

- provides a mapping from **source code** → **binary program**
- stored in extra sections in the .o files

StringRef.o

```
.text:
  _ZN4llvm9StringRef:
```

```
.debug_info:
  class StringRef {
    …
```

```
.debug_line:
0x10 StringRef.cpp  23
0x20 StringRef.h   128
…
```

Where does it go?

Option 1: linker leaves debug info in the .o files

StringRef.o

```
.text:
  _ZN4llvm9StringRef:

.debug_info:
  class StringRef {
    …

.debug_line:
0x10 StringRef.cpp   23
0x20 StringRef.h    128
…
```

PassManager.o

```
.text:

.debug_info:

.debug_line:
```

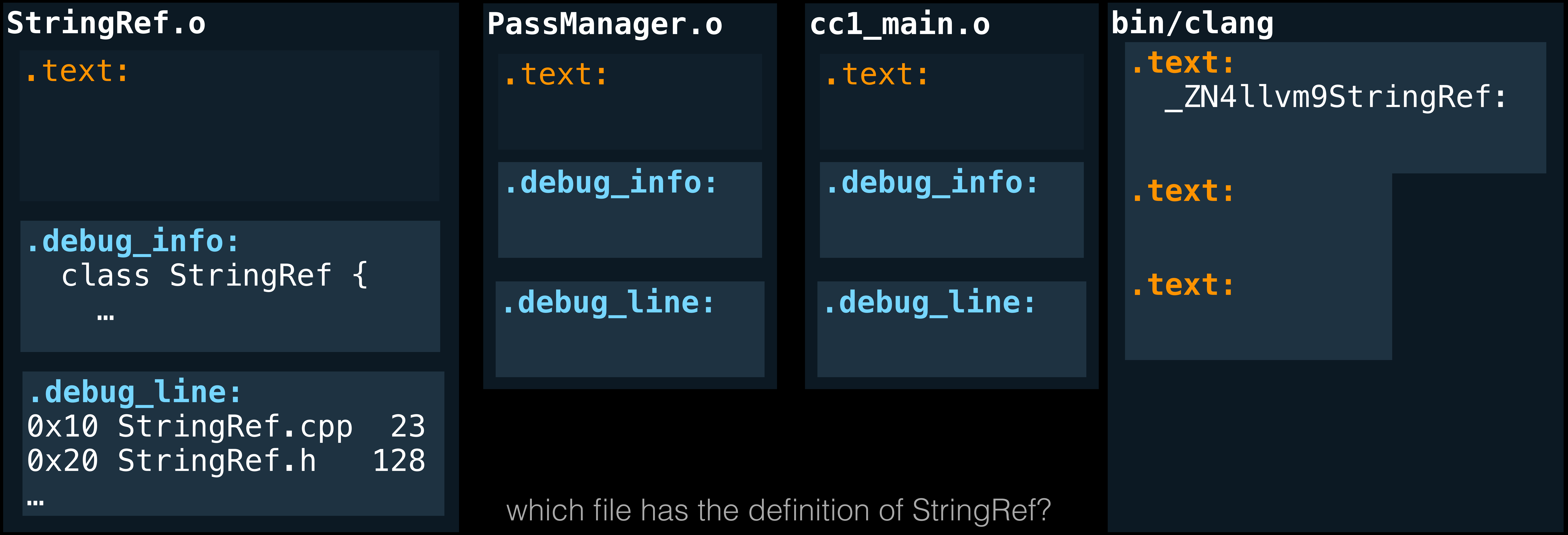
cc1_main.o

```
.text:

.debug_info:

.debug_line:
```

Where does it go?

Option 1: linker leaves debug info in the .o files

- fast linking — slow debugging



Where does it go?

Option 2: linker links debug info together with the executable

- typically done on Linux
- very long link times

Where does it go?

Option 2: linker links debug info together with the executable

- typically done on Linux
- very long link times
- split DWARF
  - relocatable **skeleton** linked with executable
  - bulk in external .dwo

```
bin/clang

.text:

.debug_info:

.debug_line:
```

```
StringRef.dwo

.debug_info.dwo:
  class StringRef {
    …

.debug_line.dwo:
x+0x0 StringRef.cpp 23
x+0x10 StringRef.h 128
…
```

Where does it go?

Option 3: debug info archived separately from executable

```
StringRef.o

.text:
  _ZN4llvm9StringRef:

.debug_info:
  class StringRef {
    …

.debug_line:
0x10 StringRef.cpp 23
0x20 StringRef.h  128
…
```

```
PassManager.o

.text:

.debug_info:

.debug_line:
```

```
cc1_main.o

.text:

.debug_info:

.debug_line:
```

Where does it go?

Option 3: debug info archived separately from executable

1. dsymutil (Darwin)

2. dwp (Linux)

```
bin/clang
  .text:
    _ZN4llvm9StringRef:
```

```
clang.dSYM / clang.dwp
  .debug_info:
    class StringRef {
      …

  .debug_line:
  0x10 StringRef.cpp 23
  0x20 StringRef.h   128
  …
```

Why is `clang.dSYM` 1.2GB?

- the problem is type information, specifically, **redundant type information**:
  - `#include “llvm/ADT/StringRef.h”` at `-g` recursively pulls in ~46KB of types into each `.o` file and there are ~1500 `.o` files

(llvm-)dsymutil

- a new linker for debug information built on top of LLVM
- dsymutil collects debug info from all the `.o` files and generates a single **`.dSYM` bundle** with all the debug info and accelerator tables for fast lookup
- dsymutil performs **ODR type uniquing** for C++

(llvm-)dsymutil

ninja clang (1561 targets)	clang.dSYM -no-odr	clang.dSYM
Regular	1.2G	413M
LTO	369M	388M

measured on a 2013 Mac Pro with 12 cores at 2.7GHz and 32GB RAM
clang r250459, X86/ARM/AArch64, RelWithDebInfo+Assertions, 1 parallel LTO link

-flimit-debug-info

(also known as `-fno-standalone-debug`)

- emit C++ class types only in the `.o` file that has the vtable of the class or an explicit template instantiation and **forward declarations** everywhere else
  - only C++ classes with vtables / explicit template instantiations
  - every .o file and (3rd-party) library must be built with debug info
  - debugger must scan every `.o` file for the definition of `StringRef`
    (LLDB does not even support that)
- Darwin and FreeBSD default to `-fstandalone-debug`

-flimit-debug-info

ninja clang (1561 targets)	_build/lib	clang.dSYM
Standalone	4.1G	413M
Limited	3.1G	402M
LTO	_build/lib	clang.dSYM
Standalone	5.1G	388M
Limited	3.9G	387M

measured on a 2013 Mac Pro with 12 cores at 2.7GHz and 32GB RAM
clang r250459, X86/ARM/AArch64, RelWithDebInfo+Assertions, 1 parallel LTO link

Clang Modules

- Clang Modules are a saner alternative to textual `#include`
- think of them as **precompiled headers** + additional semantics
- on disk: `.pcm` file with the **serialized Clang AST** of header files
  - Darwin: built implicitly and stored in a global module cache
  - Linux: typically built explicitly

Module Debugging

- build **Debug Info** together with the **Clang Module**
- new driver option: `-gmodules`
  cc1: `-dwarf-ext-refs -fmodule-format=obj`
  - emit COFF/ELF/Mach-O Module containers with a `.clang_ast` section holding the AST.
  - emit full debug information for every type in the module
  - debug info contributes ~15% of the `.pcm` size

```
LLVM_Utils.pcm

.clang_ast:
  class StringRef {
    …

.debug_info:
  class StringRef {
    …
```

Module debugging also works with precompiled headers

Reminder: -flimit-debug-info

use: forward declaration

TableGen.o

```
.text:
 call _ZN4llvm9StringRef…

.debug_info:

      namespace {
        class StringRef;
      }
```

definition

StringRef.o

```
.text:
 …

.debug_info:

      namespace llvm {
       class StringRef {
         StringRef(const char*);
          …
```

Module Debugging

use: forward declaration

TableGen.o

```
.text:
 call _ZN4llvm9StringRef…

.debug_info:
  module LLVM_Utils {
    module ADT {
      namespace {
        class StringRef;
      }
    }
 }
 dwo_name = LLVM_Utils.pcm
 dwo_id = <module_hash>
```

metadata for rebuilding module for header file

split DWARF for locating module debug info on disk

definition

LLVM_Utils.pcm

```
.clang_ast:
 …

.debug_info:
  module LLVM_Utils {
    module ADT {
      namespace llvm {
       class StringRef {
         StringRef(const char*);
          …
```

dsymutil and Clang Modules

- dsymutil clones the debug info from all imported modules into the `.dSYM` bundle bottom-up
- meanwhile using "ODR" type uniquing to **resolve** all **forward declarations**
  - top-level modules are unique: this works for C, C++ and Objective-C
- consumers of the resulting `.dSYM` need not know about modules

clang.dSYM

```
.debug_info:
module Darwin {
  module C {
    module stdint { … }
    …
  }
}
module std {
  …
  module vector { … }
}
module LLVM_Utils { … }
…
StringRef(const char*)
```

dsymutil and Clang Modules

ninja clang (1561 targets)	Wall Clock	_build/lib
Standalone	7m 30s	4.1G

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dsymutil and Clang Modules

ninja clang (1561 targets)	Wall Clock	_build/lib
Standalone	7m 30s	4.1G

LTO	Wall Clock	_build/lib
Standalone	26m 39s	5.1G

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dsymutil and Clang Modules

ninja clang (1561 targets)	Wall Clock	_build/lib
Standalone	7m 30s	4.1G
Limited	7m 23s	3.1G

LTO	Wall Clock	_build/lib
Standalone	26m 39s	5.1G
Limited	26m 05s	3.9G

measured on a 2013 Mac Pro with 12 cores at 2.7GHz and 32GB RAM
clang r250459, X86/ARM/AArch64, RelWithDebInfo+Assertions, 1 parallel LTO link

dsymutil and Clang Modules

ninja clang (1561 targets)	Wall Clock	_build/lib	modules-cache
Standalone	7m 30s	4.1G	
Limited	7m 23s	3.1G	
-fmodules	6m 28s	7.2G	322M

LTO	Wall Clock	_build/lib	modules-cache
Standalone	26m 39s	5.1G	
Limited	26m 05s	3.9G	
-fmodules	31m 41s	8.9G	322M

measured on a 2013 Mac Pro with 12 cores at 2.7GHz and 32GB RAM
clang r250459, X86/ARM/AArch64, RelWithDebInfo+Assertions, 1 parallel LTO link

dsymutil and Clang Modules

ninja clang (1561 targets)	Wall Clock	_build/lib	modules-cache
Standalone	7m 30s	4.1G	
Limited	7m 23s	3.1G	
-fmodules	6m 28s	7.2G	322M
-gmodules	4m 54s	1.2G	368M
LTO	Wall Clock	_build/lib	modules-cache
Standalone	26m 39s	5.1G	
Limited	26m 05s	3.9G	
-fmodules	31m 41s	8.9G	322M
-gmodules	20m 35s	1.6G	369M

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dsymutil and Clang Modules

ninja clang (1561 targets)	Wall Clock	_build/lib	modules-cache	clang.dSYM
Standalone	7m 30s	4.1G		413M
Limited	7m 23s	3.1G		402M
-fmodules	6m 28s	7.2G	322M	564M
-gmodules	4m 54s	1.2G	368M	453M
LTO	**Wall Clock**	**_build/lib**	**modules-cache**	**clang.dSYM**
Standalone	26m 39s	5.1G		388M
Limited	26m 05s	3.9G		387M
-fmodules	31m 41s	8.9G	322M	381M
-gmodules	20m 35s	1.6G	369M	407M

measured on a 2013 Mac Pro with 12 cores at 2.7GHz and 32GB RAM
clang r250459, X86/ARM/AArch64, RelWithDebInfo+Assertions, 1 parallel LTO link

What if consumers know about Modules?

- **LLDB** is built on top of Clang
- when evaluating an expression, LLDB
  1. loads type info from DWARF
  2. builds a Clang AST
  3. compiles and executes the Clang AST

What if consumers know about Modules?

- **LLDB** is built on top of Clang
- when evaluating an expression, LLDB
  1. ~~loads type info from DWARF~~
  2. ~~builds a Clang AST~~
  3. compiles and executes the Clang AST

a module-aware LLDB

- imports the type's AST from the Clang Module

Questions?