Fine-grained Compilation Caching using llvm-cas

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LLVM Dev Meeting 2024

Background

- This talk is about compilation caching, using a Content Addressable Storage (CAS)

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Past LLVM Dev Meeting Talks

LLVM Dev 2023: Representing Debug Info in LLVM CAS
https://www.youtube.com/watch?v=VPqZ8LoM5Z8

LLVM Dev 2022: Using Content-Addressable Storage in Clang for Caching Computations and Eliminating Redundancy
https://www.youtube.com/watch?v=E9GdNKjGZ7Y

Agenda

- Content-Addressable Storage (CAS) recap
- Improvements to `.debug_info` section representation in fine-grained object storage
- Improvements to replay speed in fine-grained object storage
- Fine-grained object storage support for Swift

Introducing MCCAS!

- One thing we are doing with a CAS is to create a build cache, comparable to ccache
- Split object files CASObjects for finer-grained object storage

ccache vs MCCAS

ccache

- Granularity: Object File level
- Higher rate of growth over incremental builds

MCCAS

- Granularity: Below Function Level
- Lower rate of growth over incremental builds

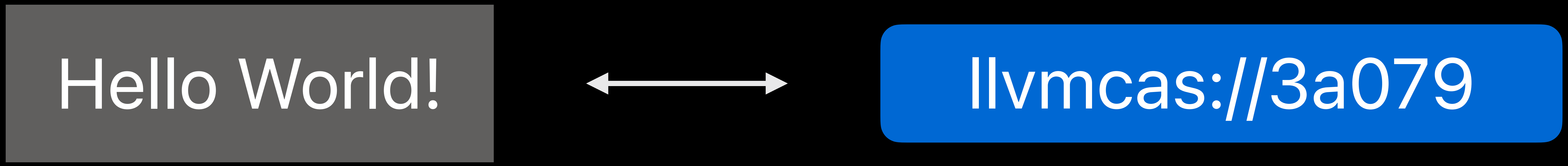
CAS Object Store refresher

CAS object address = hash of contents

CAS Object Store

CAS object address = hash of contents

1:1 mapping



CAS Object Store

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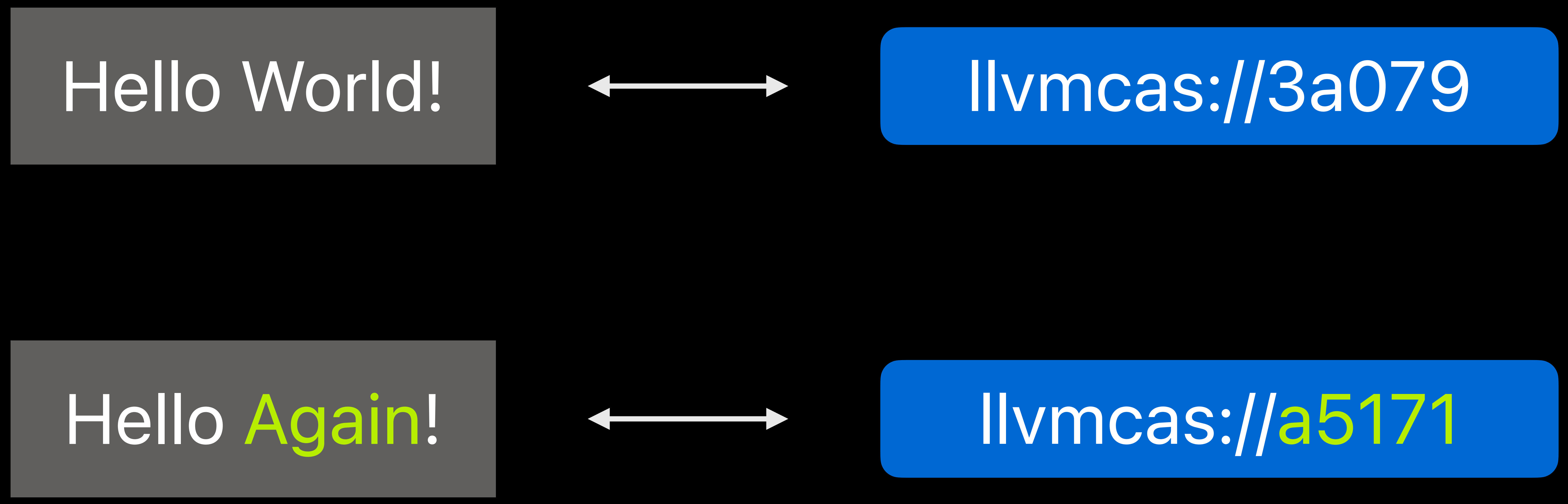
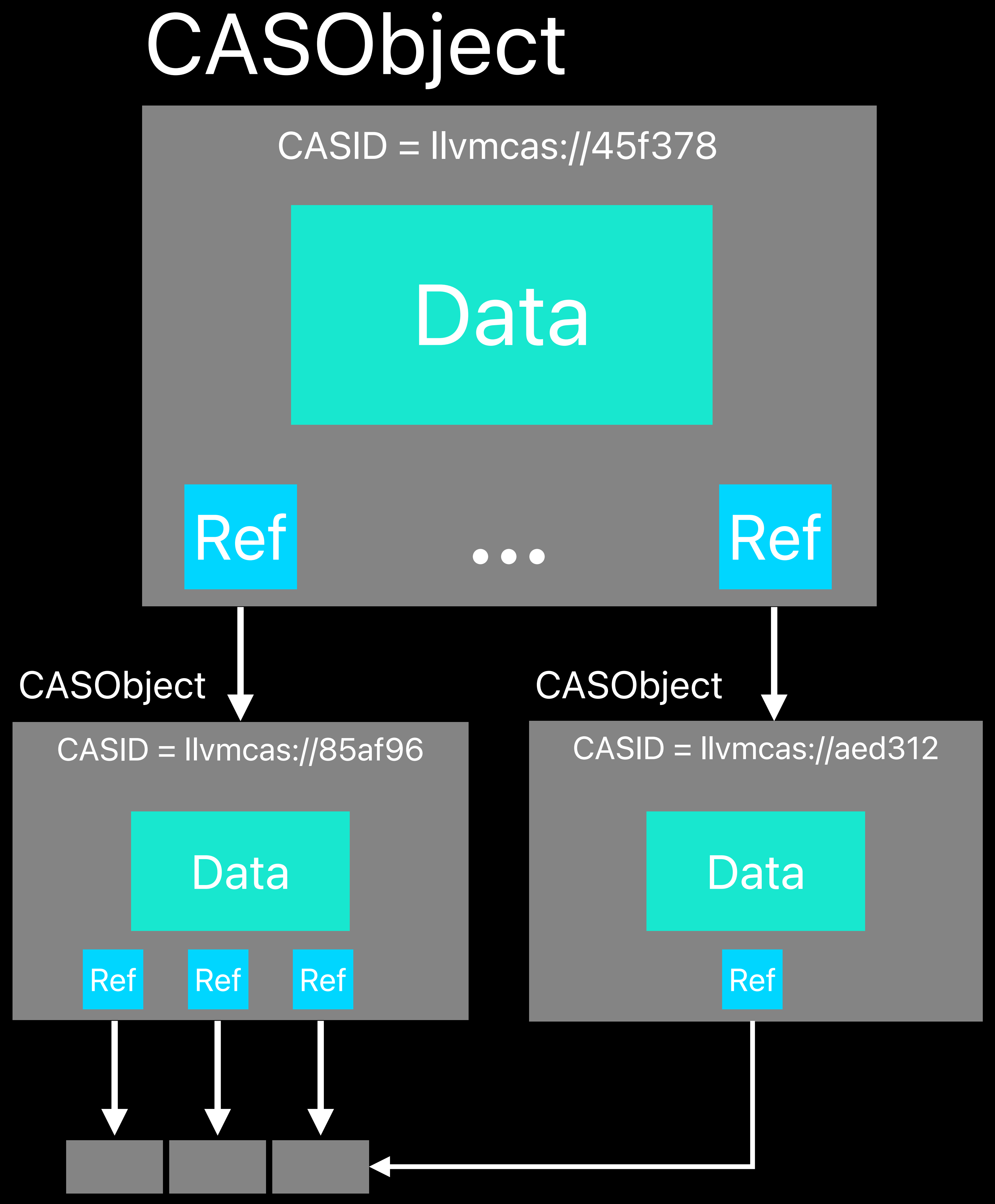


Representation of Content in the CAS

- Content is a DAG of CASObjects
- Each CASObject has data and a list of references to other CASObjects



Where we left off

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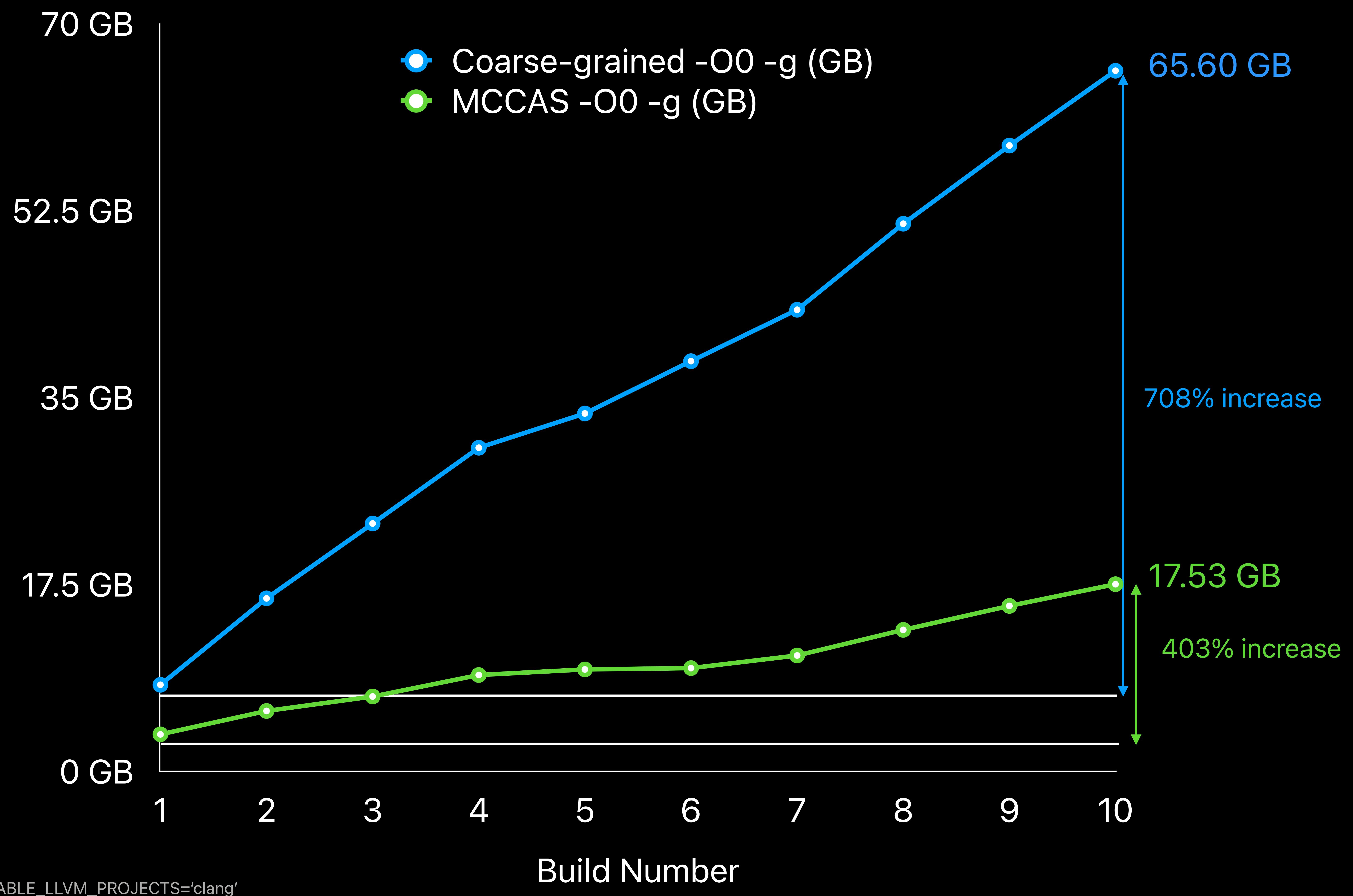

llvm-project, -DCMAKE_ENABLE_LLVM_PROJECTS='clang'

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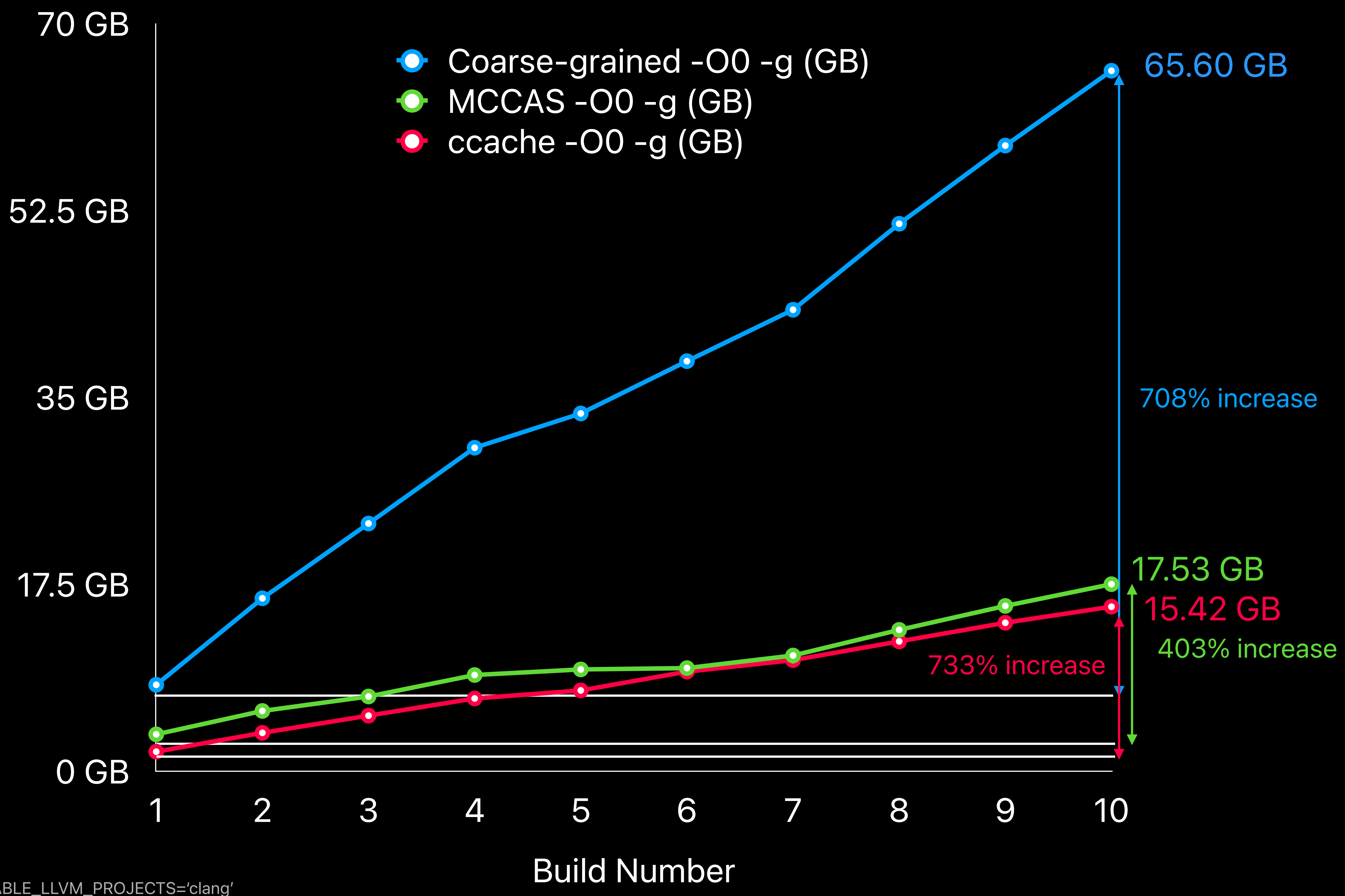

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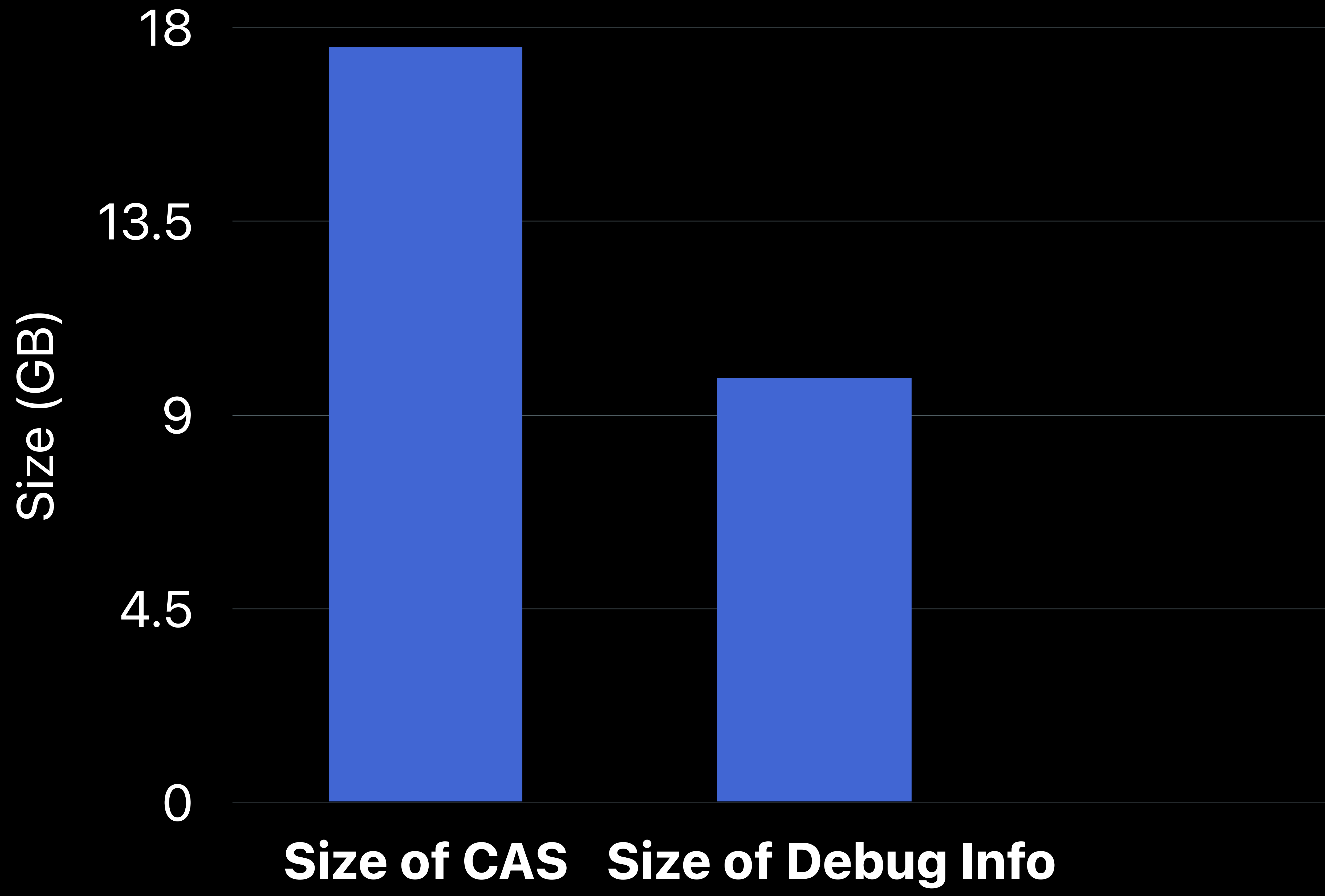
Improvements since last year

Improvements since last year

- `.debug_info` section
  >50% of the total CAS size



.debug_info representation

```
int func(int x) {
  return x+1;
}

int func2(int x) {
  return x+1;
}
```

.debug_info representation

```
dwarfdump a.o —debug-info -f func

0x25: DW_TAG_subprogram
        DW_AT_low_pc(0x…)
        DW_AT_high_pc(0x…)
        DW_AT_linkage_name("_Z4funci")
        DW_AT_name("func")
        DW_AT_decl_file("a.cpp")
        DW_AT_decl_line(1)
        DW_AT_type(“int”)
```

```
dwarfdump a.o —debug-info -f func2

0x41: DW_TAG_subprogram
        DW_AT_low_pc(0x…)
        DW_AT_high_pc(0x…)
        DW_AT_linkage_name("_Z5func2i")
        DW_AT_name("func2")
        DW_AT_decl_file("a.cpp")
        DW_AT_decl_line(5)
        DW_AT_type(“int”)
```

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Debug information is represented by Debug Information Entries or DIEs

.debug_info representation

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```
dwarfdump a.o —debug-info -f func2

0x41: DW_TAG_subprogram
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        DW_AT_decl_file("a.cpp")
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        DW_AT_type(“int”)
```

Some data in a DIE does not deduplicate, this goes into a separate CAS block called DistinctData

.debug_info representation

```
dwarfdump a.o —debug-info —f func —c

0x25: DW_TAG_subprogram
        DW_AT_low_pc(0x…)
        …
0x35:   DW_TAG_formal_parameter
          DW_AT_location(…)
          DW_AT_name(“x”)
          DW_AT_decl_file(“a.cpp”)
          DW_AT_decl_line(1)
          DW_AT_type(“int”)
```

```
dwarfdump a.o —debug-info —f func2 —c

0x41: DW_TAG_subprogram
        DW_AT_low_pc(0x…)
        …
0x51:   DW_TAG_formal_parameter
          DW_AT_location(…)
          DW_AT_name(“x”)
          DW_AT_decl_file(“a.cpp”)
          DW_AT_decl_line(1)
          DW_AT_type(“int”)
```

DIEs can have children DIEs

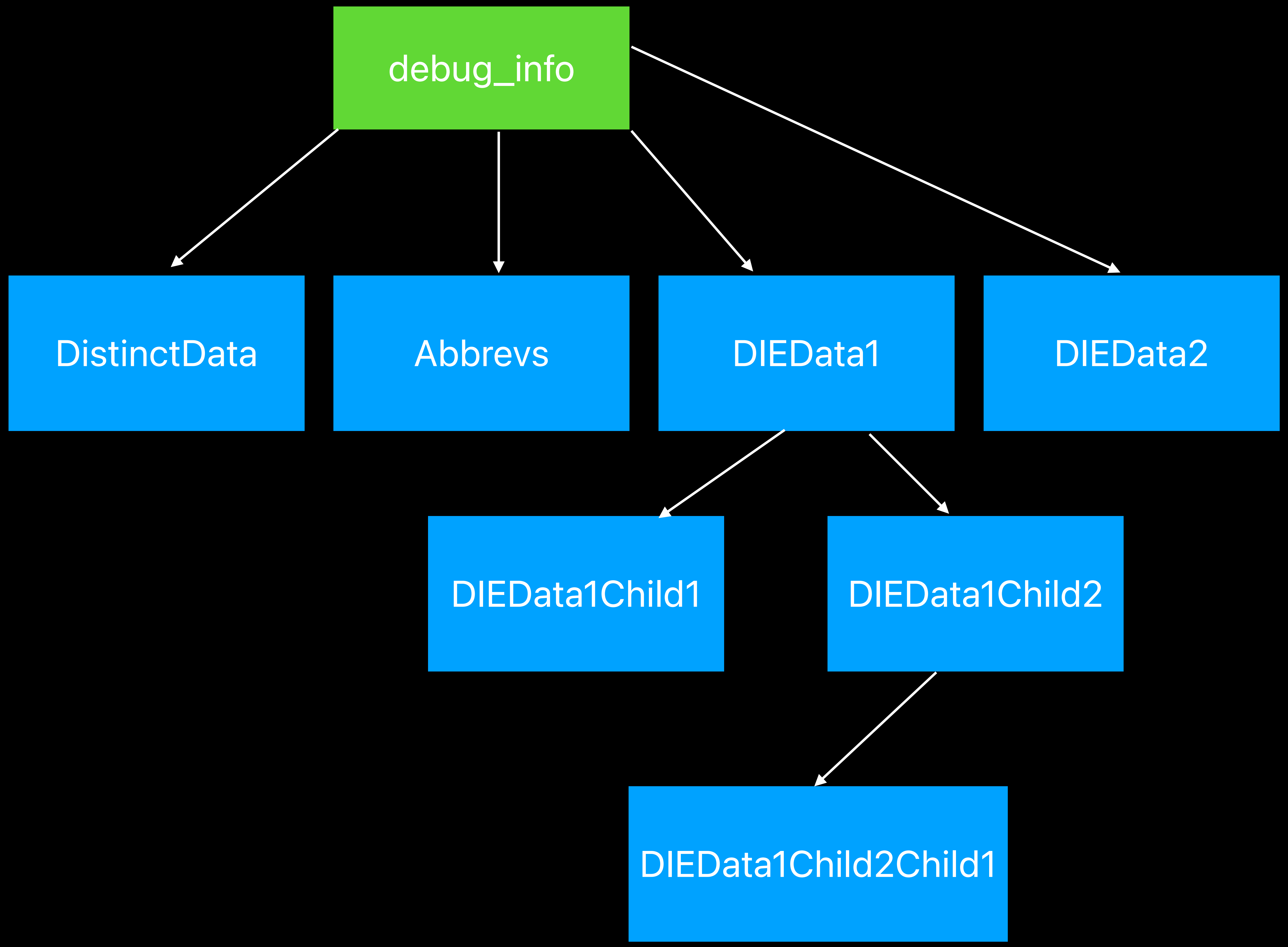
.debug_abbrev

.debug_abbrev can be thought of as the "type" of a DIE

```
dwarfdump a.o —debug-abbrev

[2] DW_TAG_subprogram
DW_CHILDREN_yes
       DW_AT_low_pc          DW_FORM_addrx
       DW_AT_high_pc         DW_FORM_data4
       DW_AT_linkage_name    DW_FORM_strx1
       DW_AT_name            DW_FORM_strx1
       DW_AT_decl_file       DW_FORM_data1
       DW_AT_decl_line       DW_FORM_data1
       DW_AT_type            DW_FORM_ref4
```

Debug Information representation during LLVM Dev Meeting 2023



`.debug_info` representation improvements

Two main improvements in `.debug_info` representation

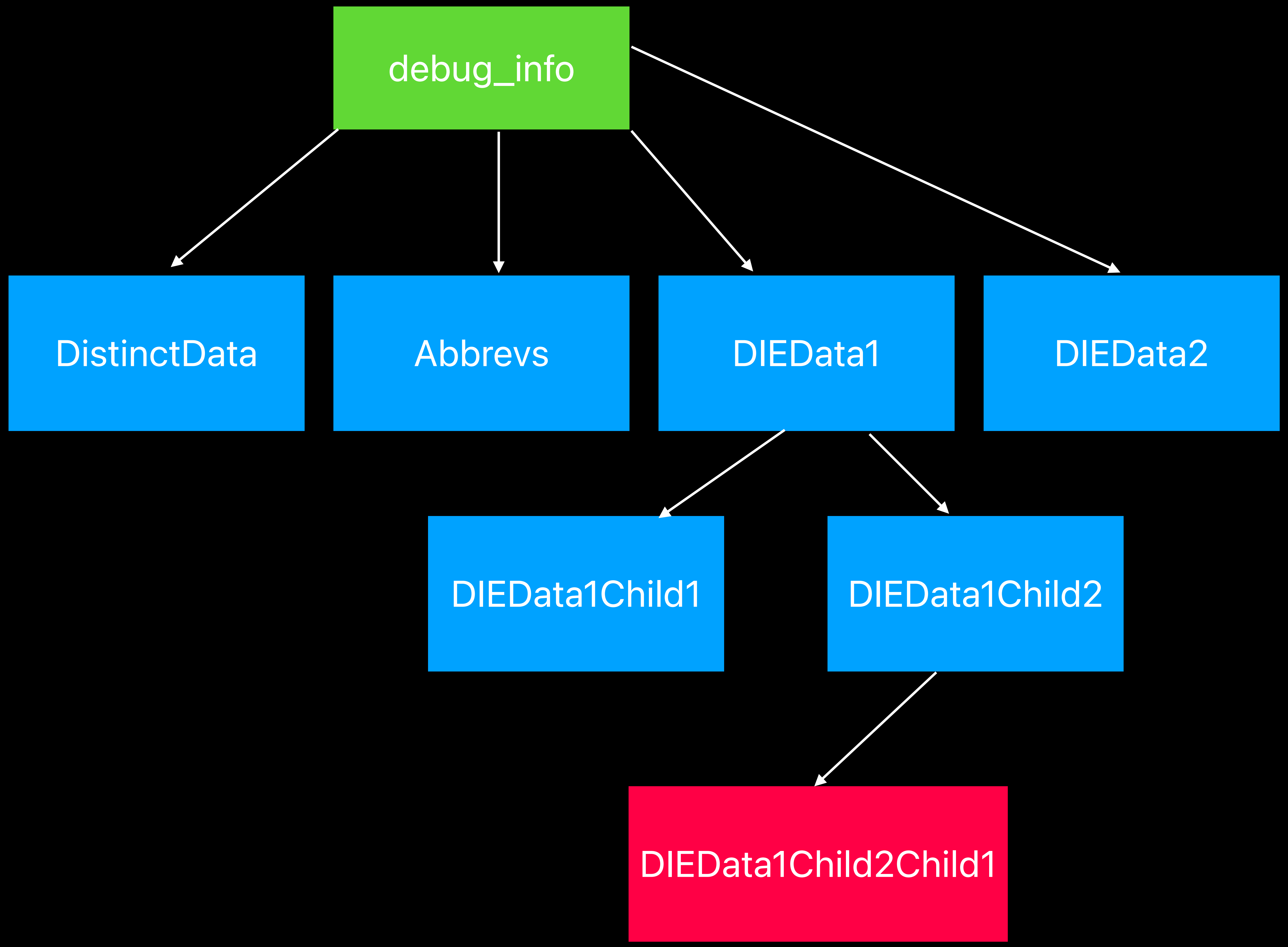
- Flattening of the `.debug_info` section CAS layout
- Reduction of the size of the *DistinctData* CAS Object, via compression

Debug Information representation during LLVM Dev Meeting 2023

Flattening of the Debug Information section representation

- CAS Object’s Address = Hash of its contents
- CAS Object’s contents is the data, ***and*** the list of references to other CAS Objects
- Also, CAS Blocks are always ordered

Debug Information representation during LLVM Dev Meeting 2023



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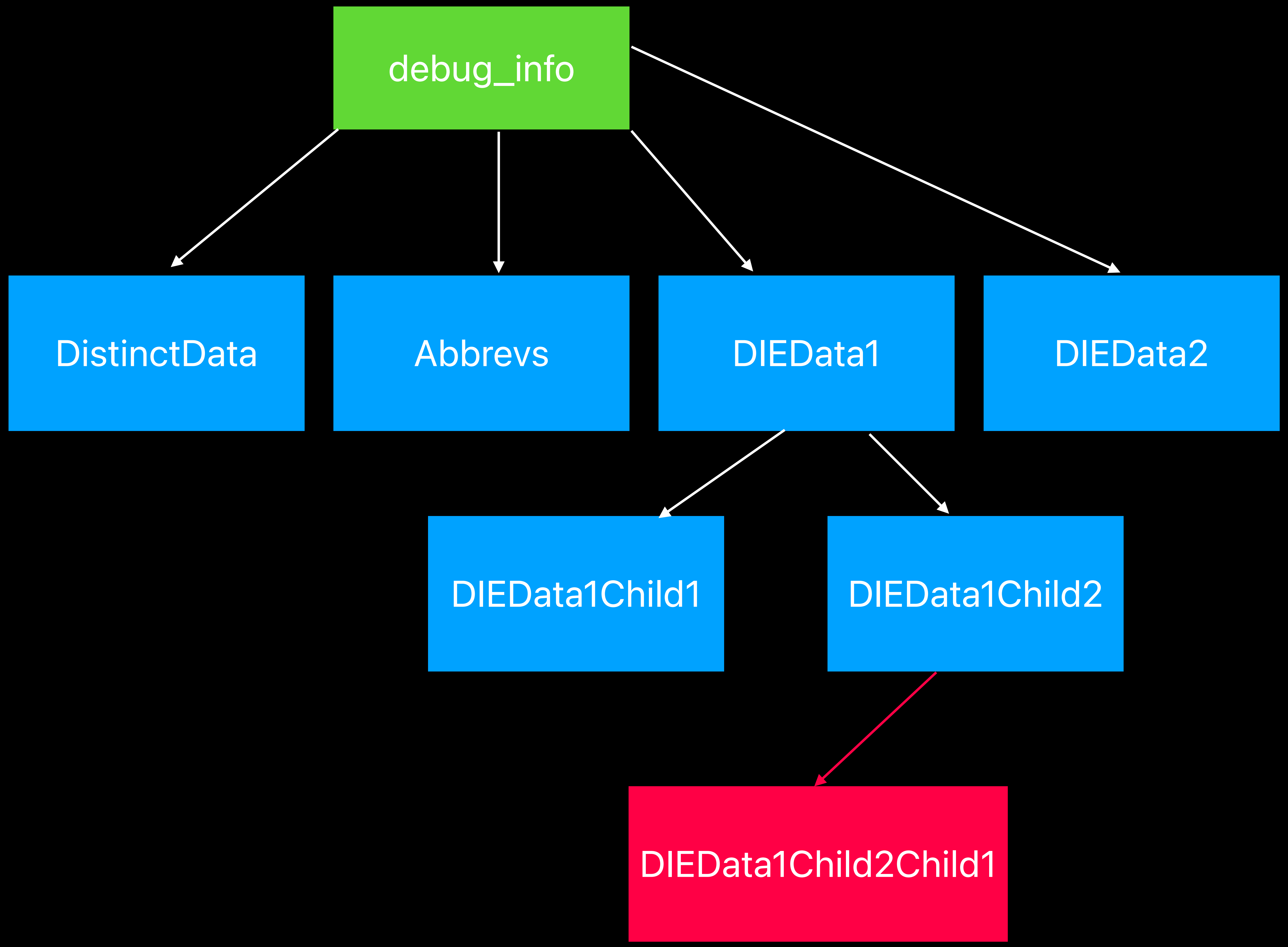

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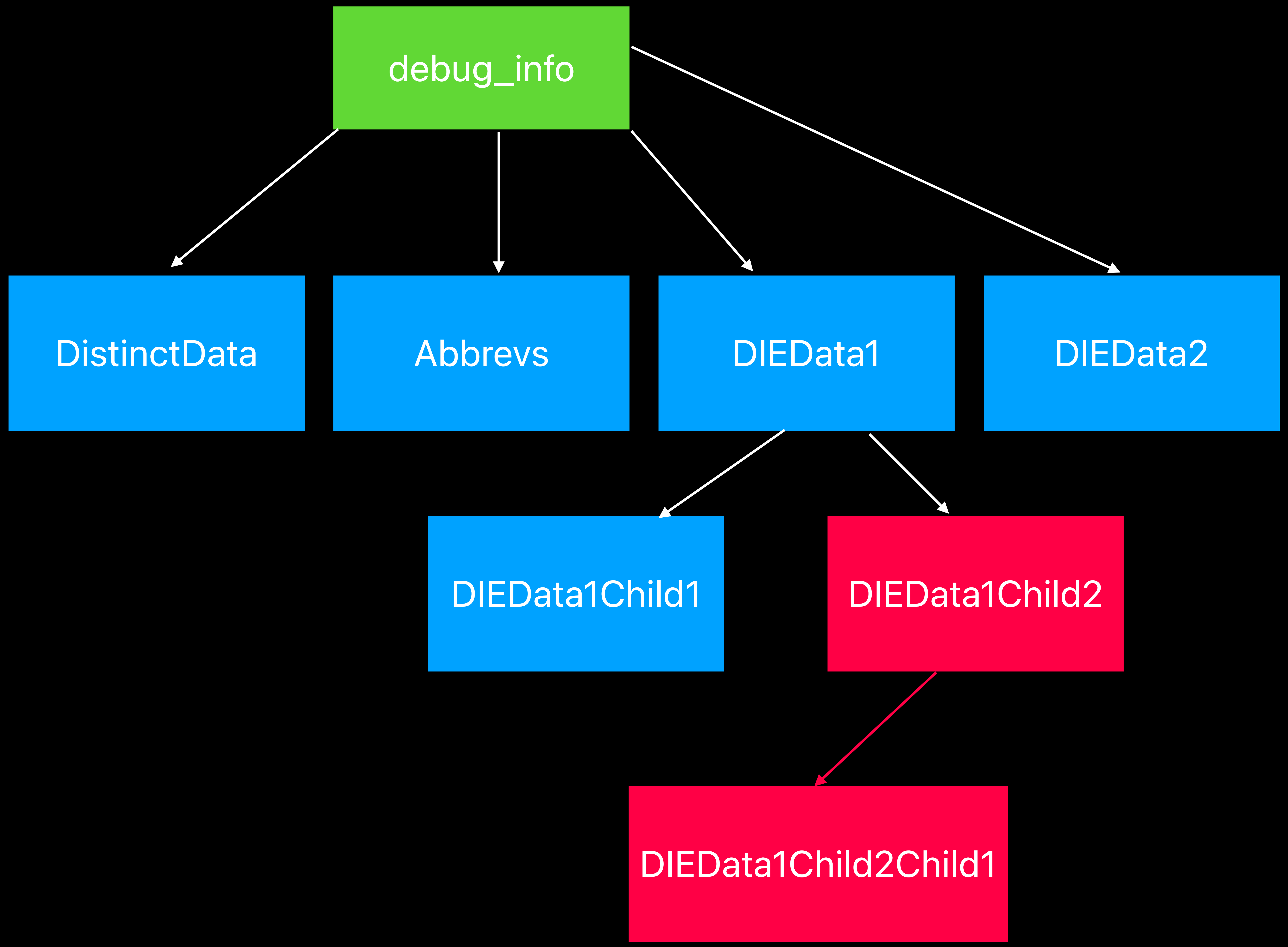

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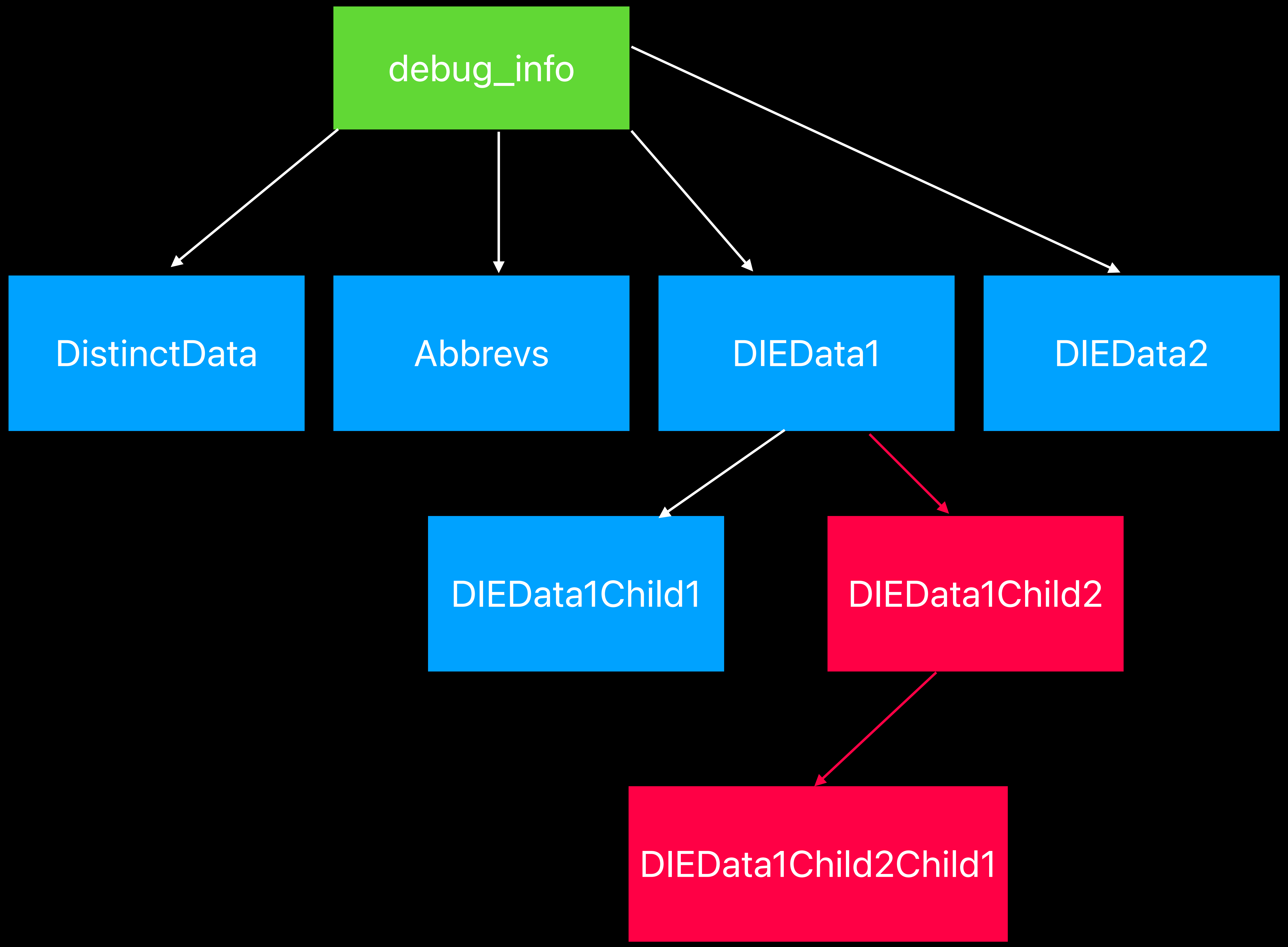

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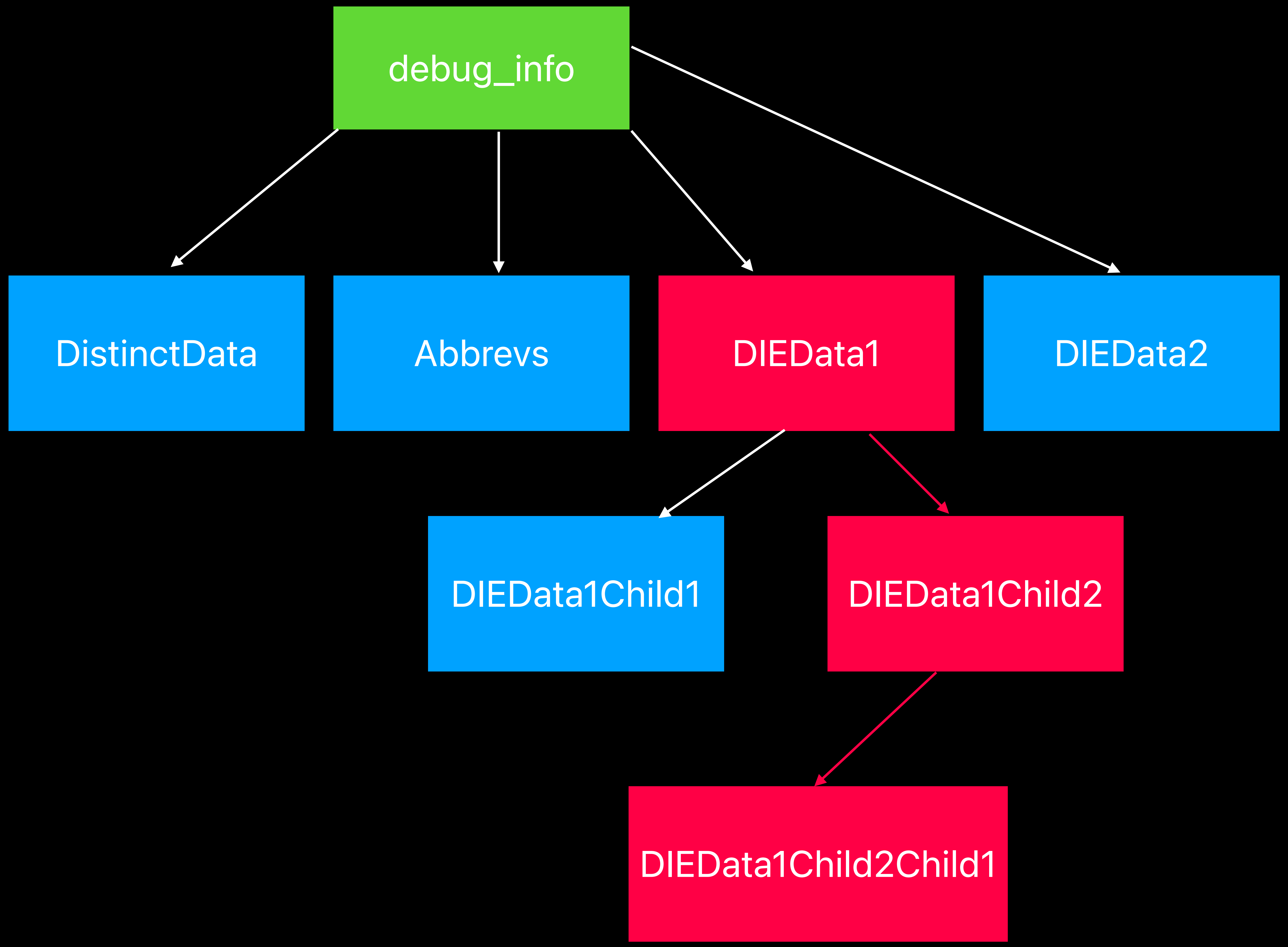

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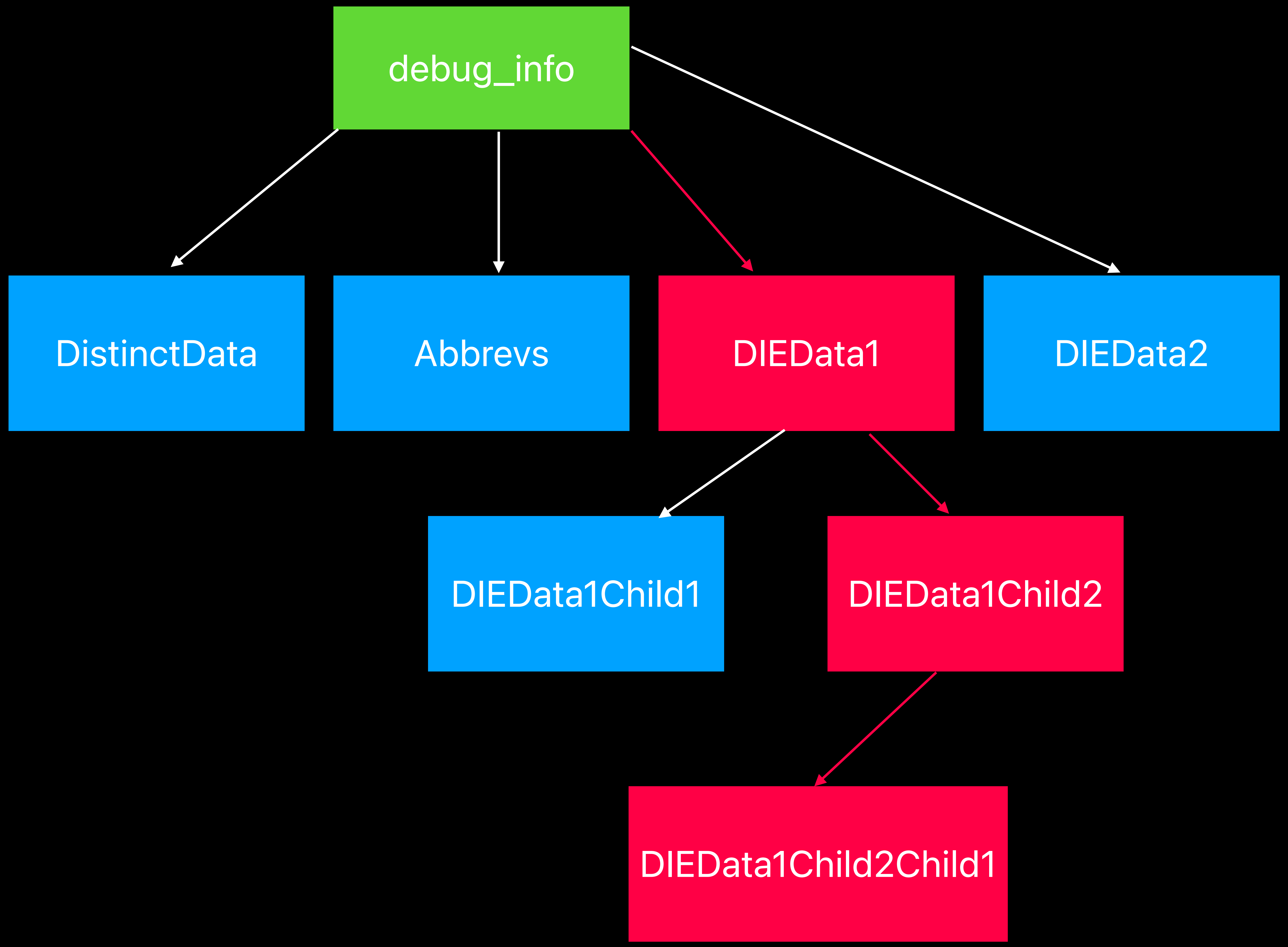
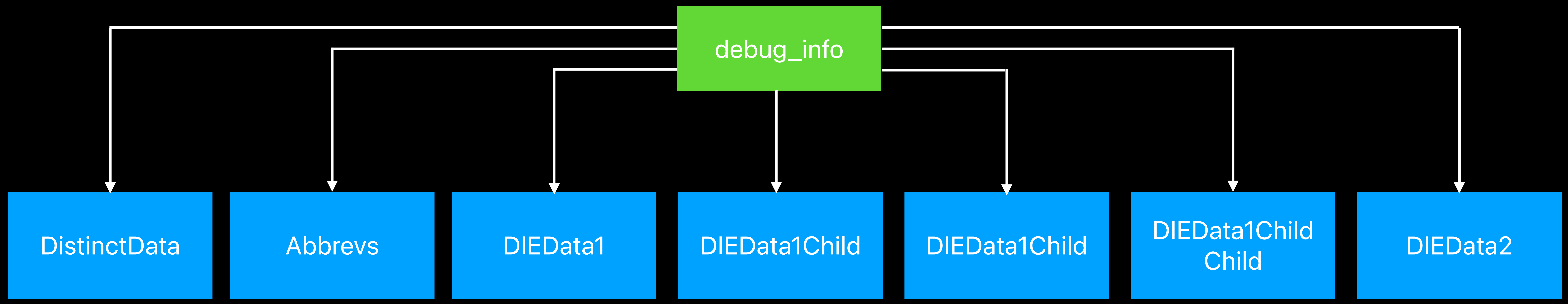


New representation

Flattening of the Debug Information section representation



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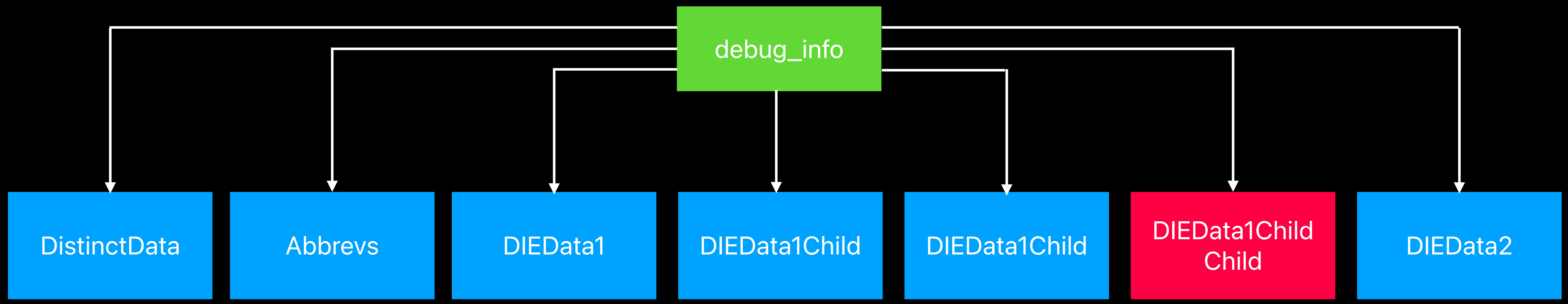

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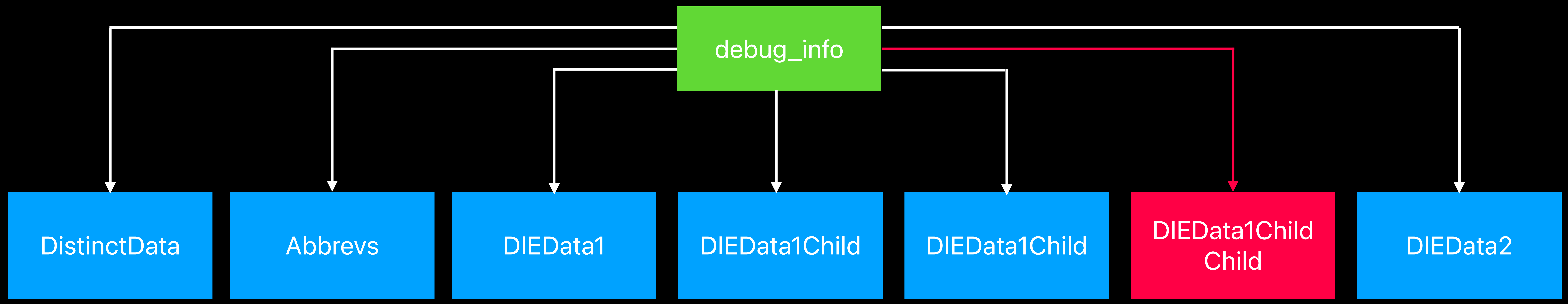
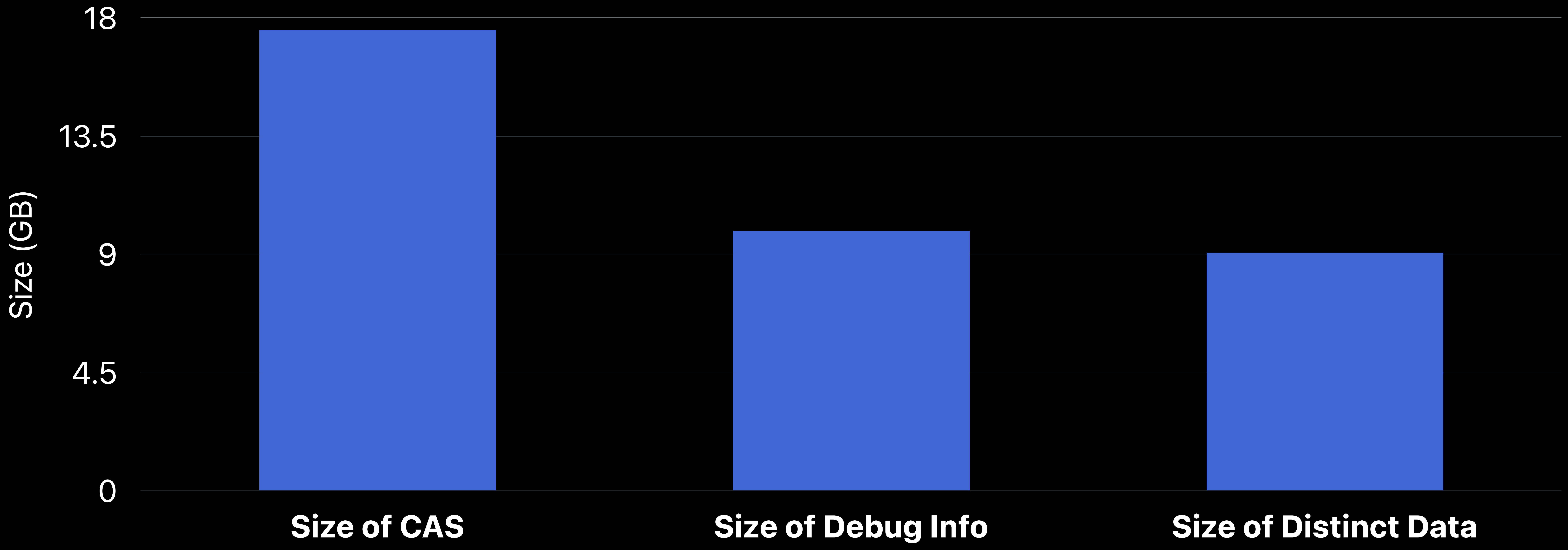


Adding Compression

Reduction of the size of the DistinctData CAS Object block via compression



Debug Information representation improvements

Reduction of the size of the DistinctData CAS Object block via compression

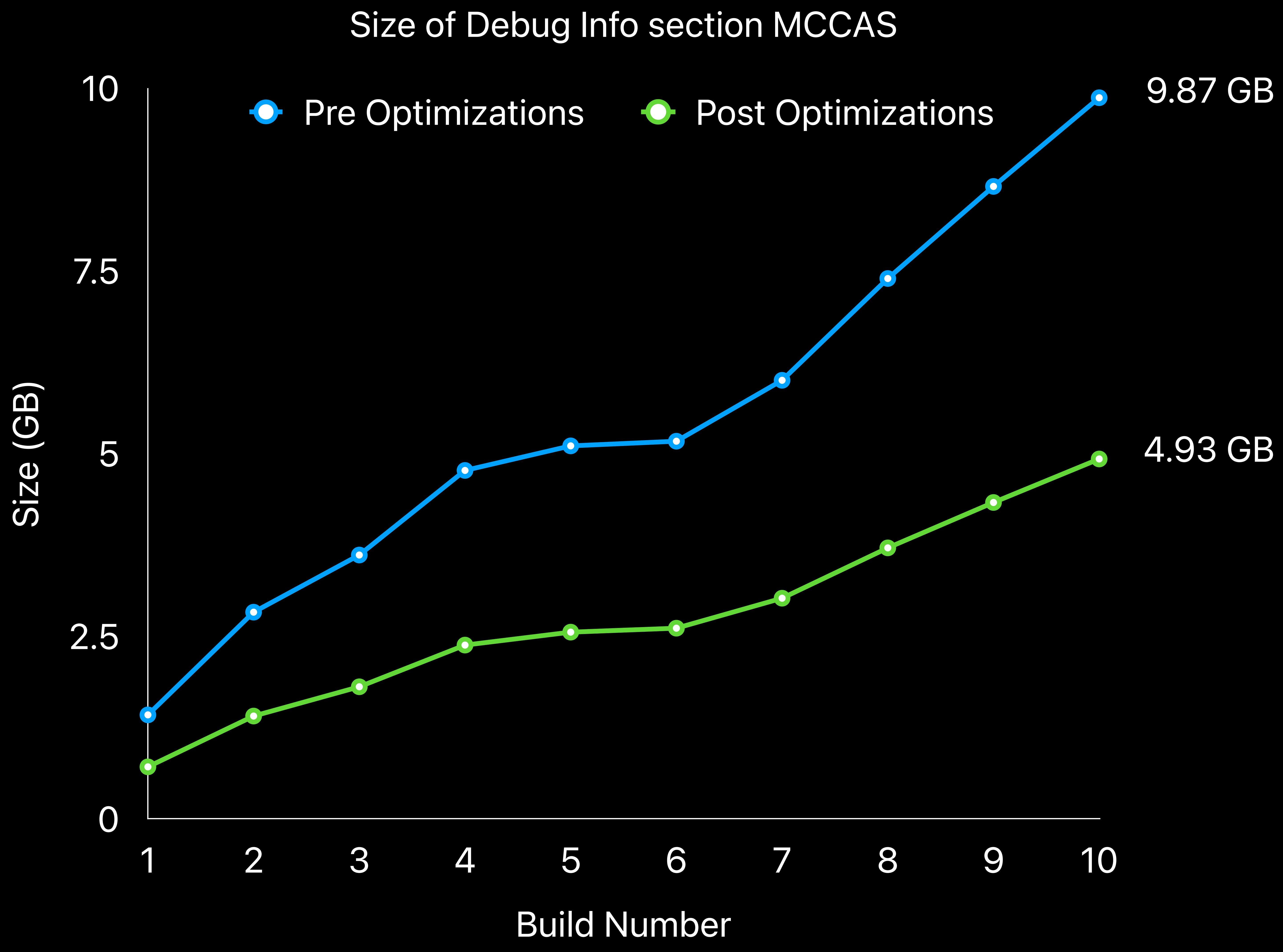
- *DistinctData* block stores all the data that doesn't deduplicate
- Accounts for 90% of `.debug_info` in CAS

Debug Information representation improvements

Reduction of the size of the DistinctData CAS Object block via compression

- *DistinctData* block stores all the data that doesn’t deduplicate
- Accounts for 90% of `.debug_info` in CAS
- Only one *DistinctData* block per object file
  - 9.07 GB = 14370 CAS Blocks, or 630 KB per Block

Debug Information representation improvements: Results



llvm-project, -DCMAKE_ENABLE_LLVM_PROJECTS='clang'

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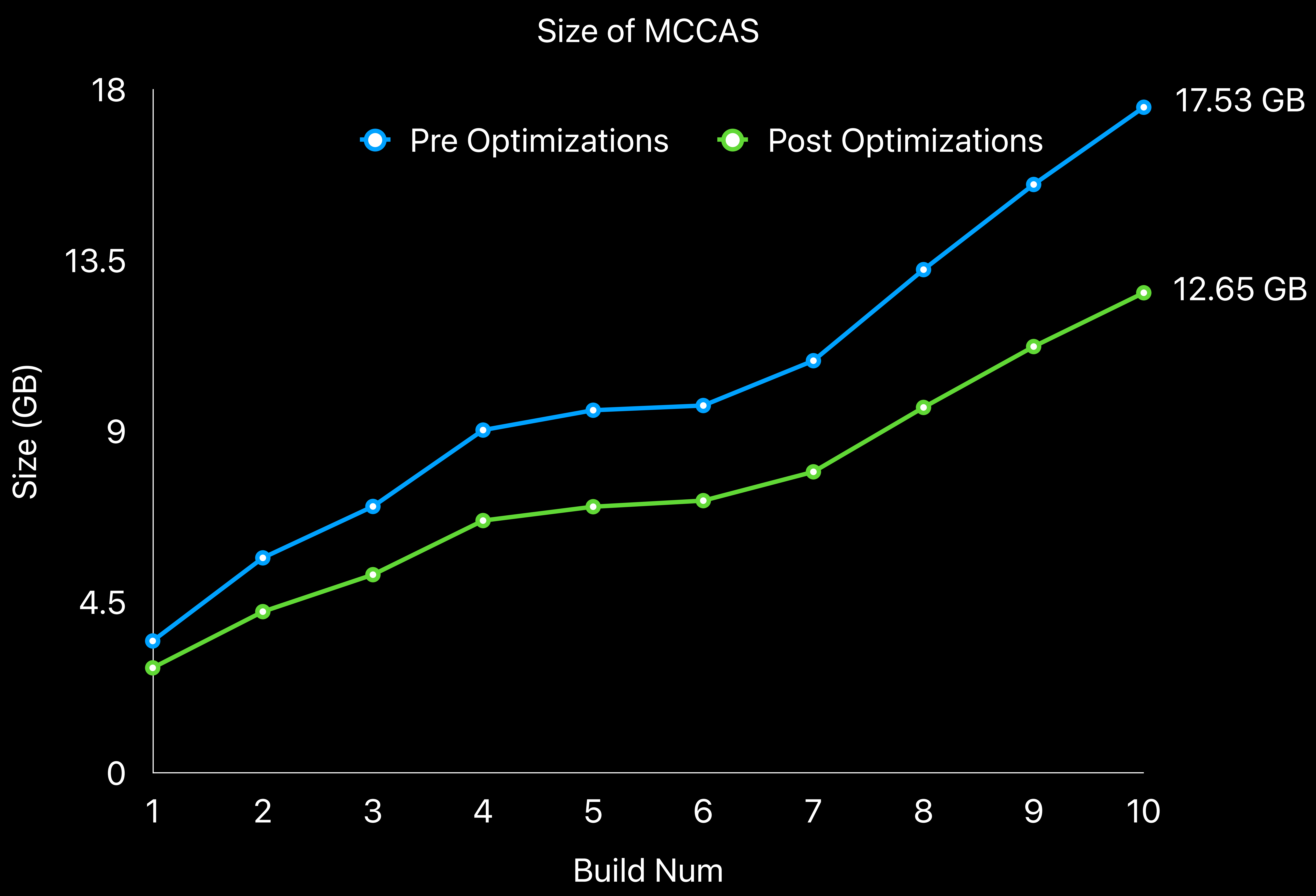

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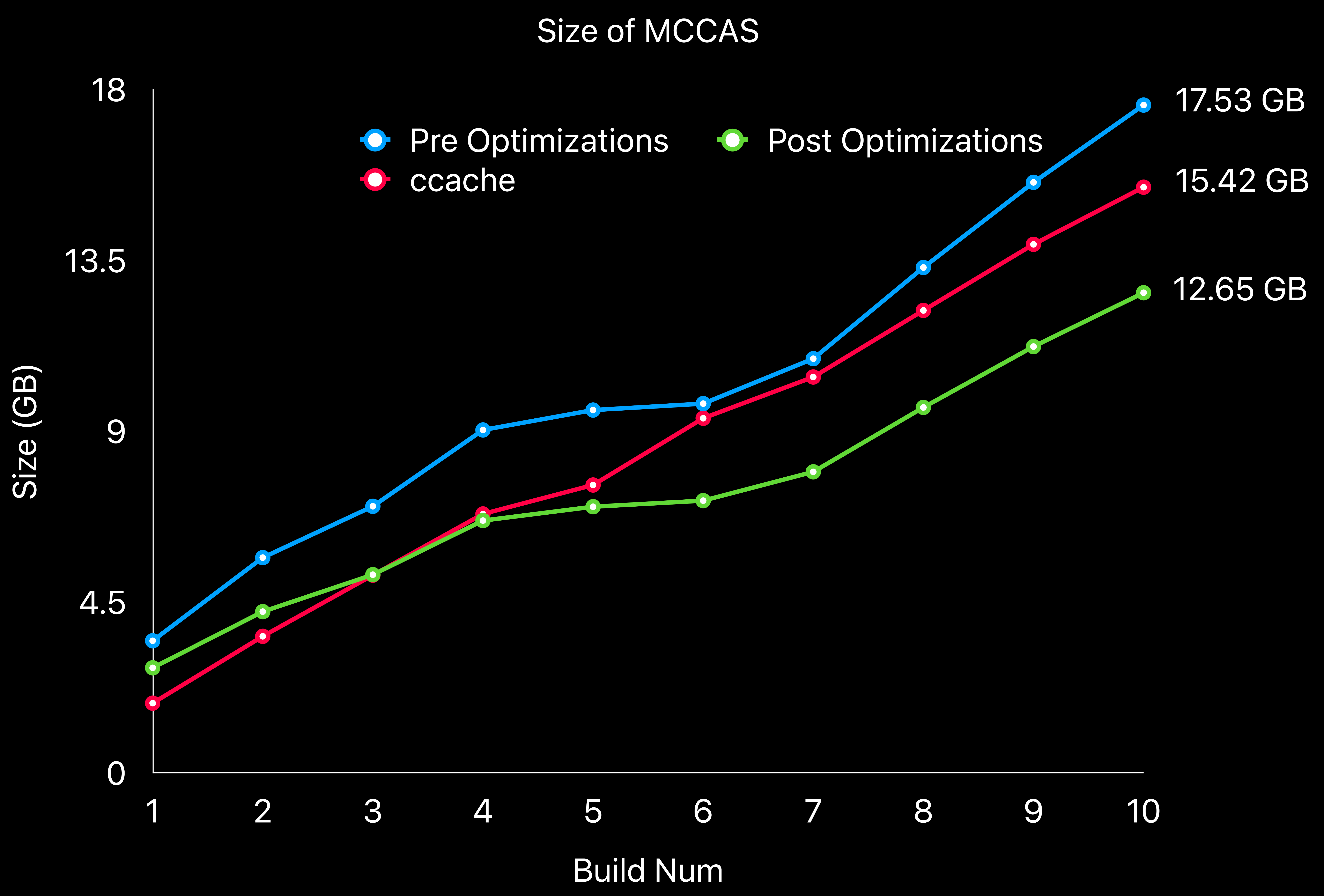

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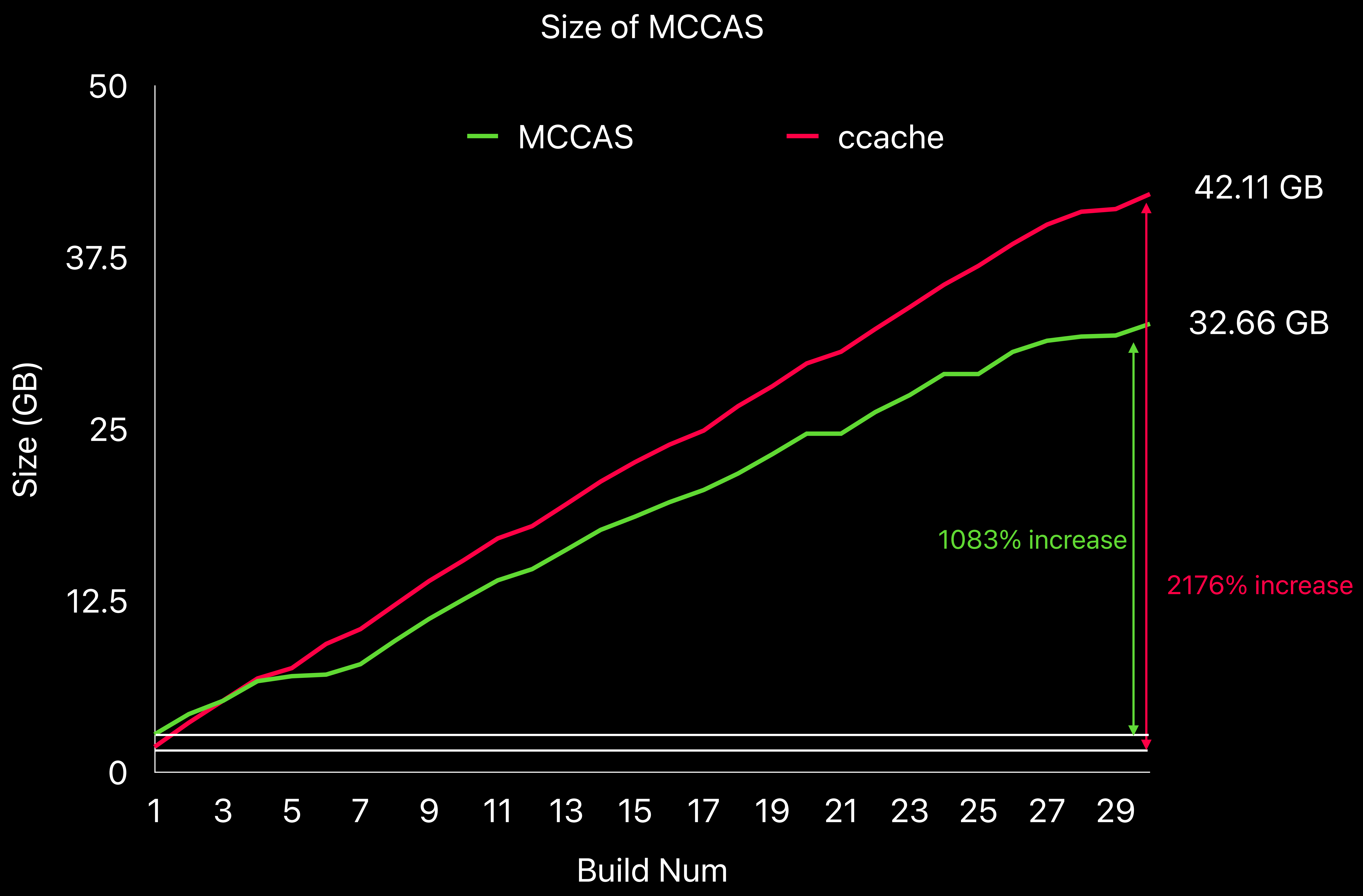

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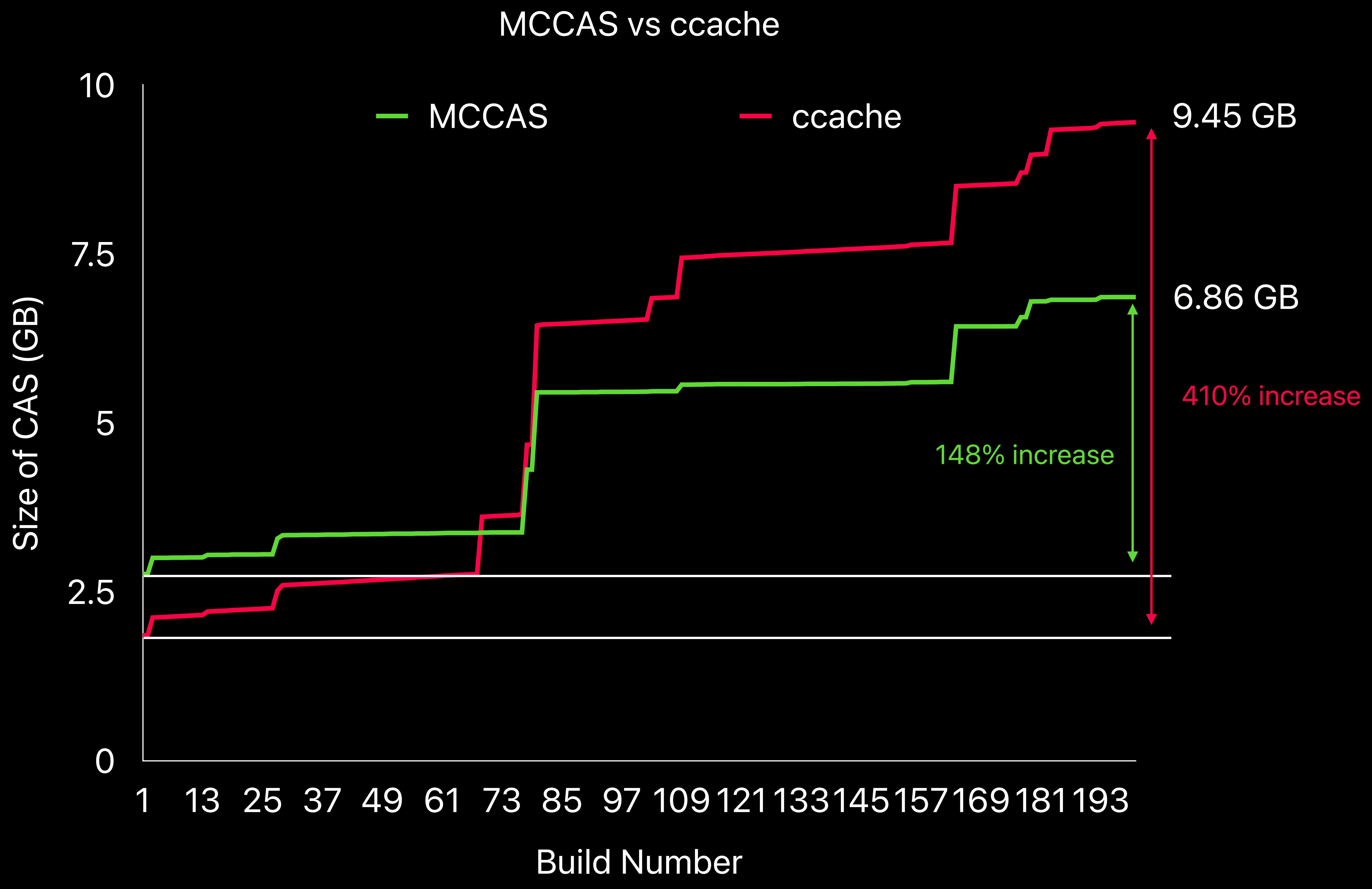

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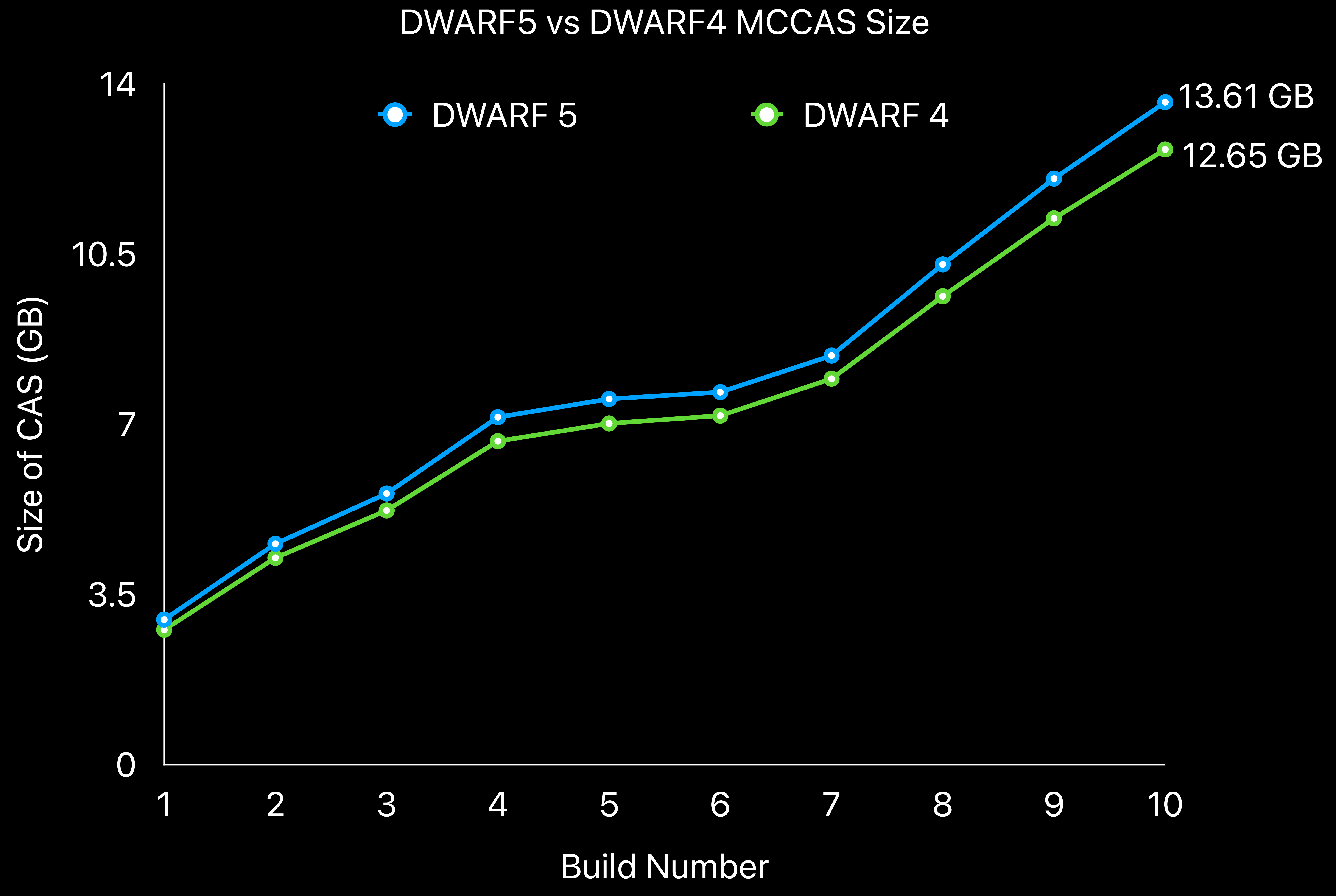
Support for DWARF5 in MCCAS

Support for DWARF5 in MCCAS: Results



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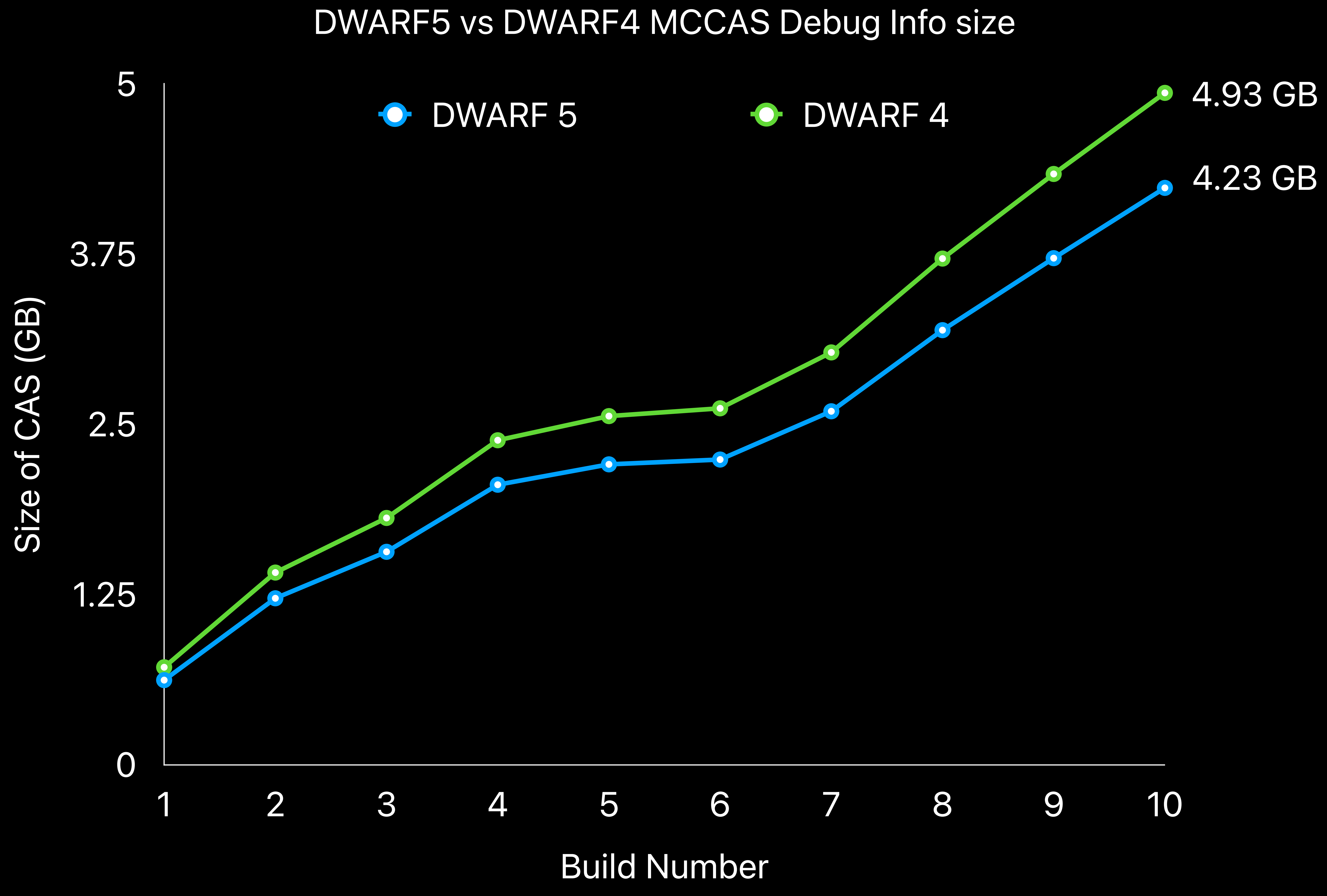

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Support for DWARF5 in MCCAS: Results

- DWARF5 CAS 7% > DWARF4 CAS
- Reason is `.debug_str_offsets` section in DWARF5

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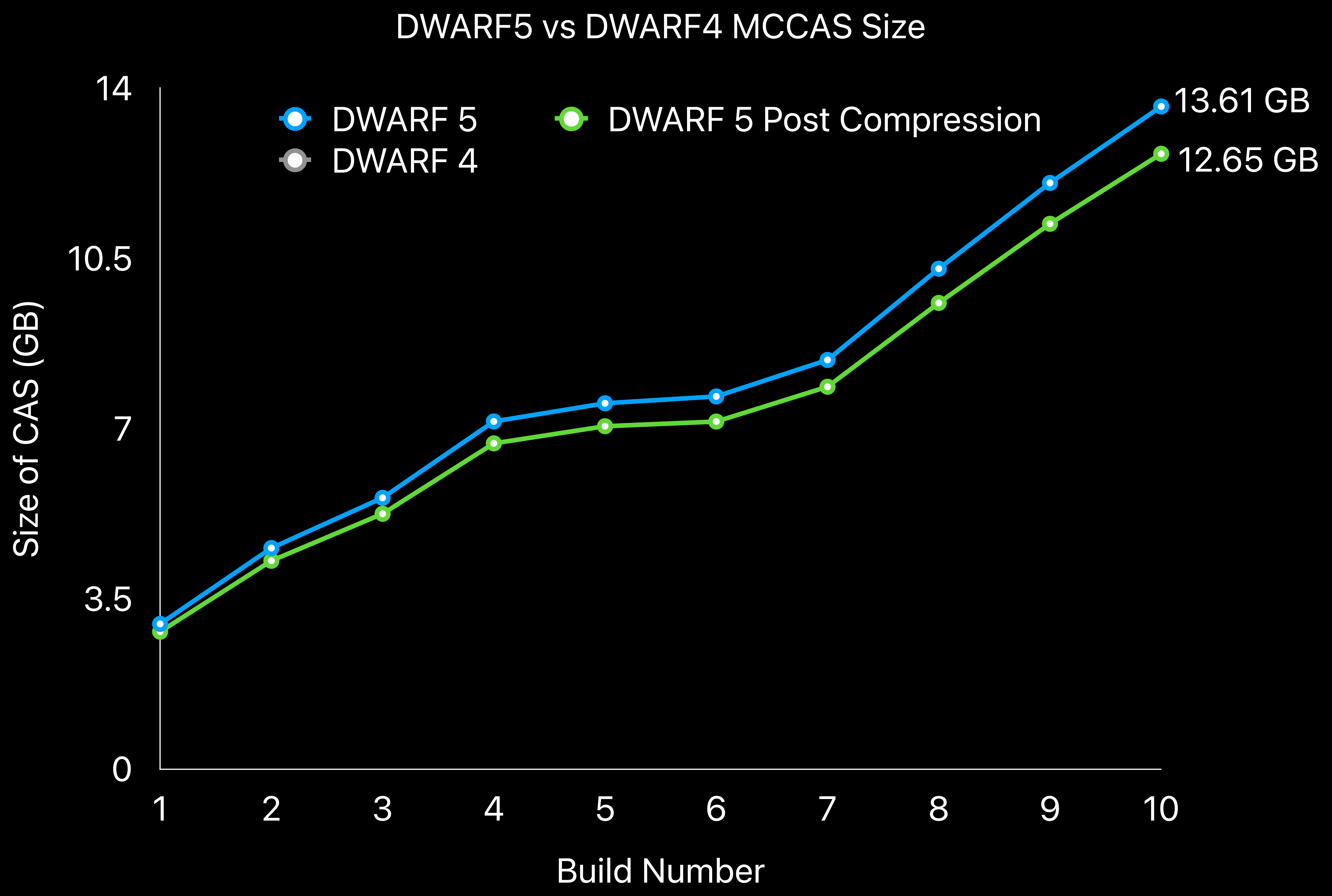
- DWARF5 CAS 7% > DWARF4 CAS
- Reason is `.debug_str_offsets` section in DWARF5
- Zlib compression brings size down to DWARF4 levels

Support for DWARF5 in MCCAS: Results



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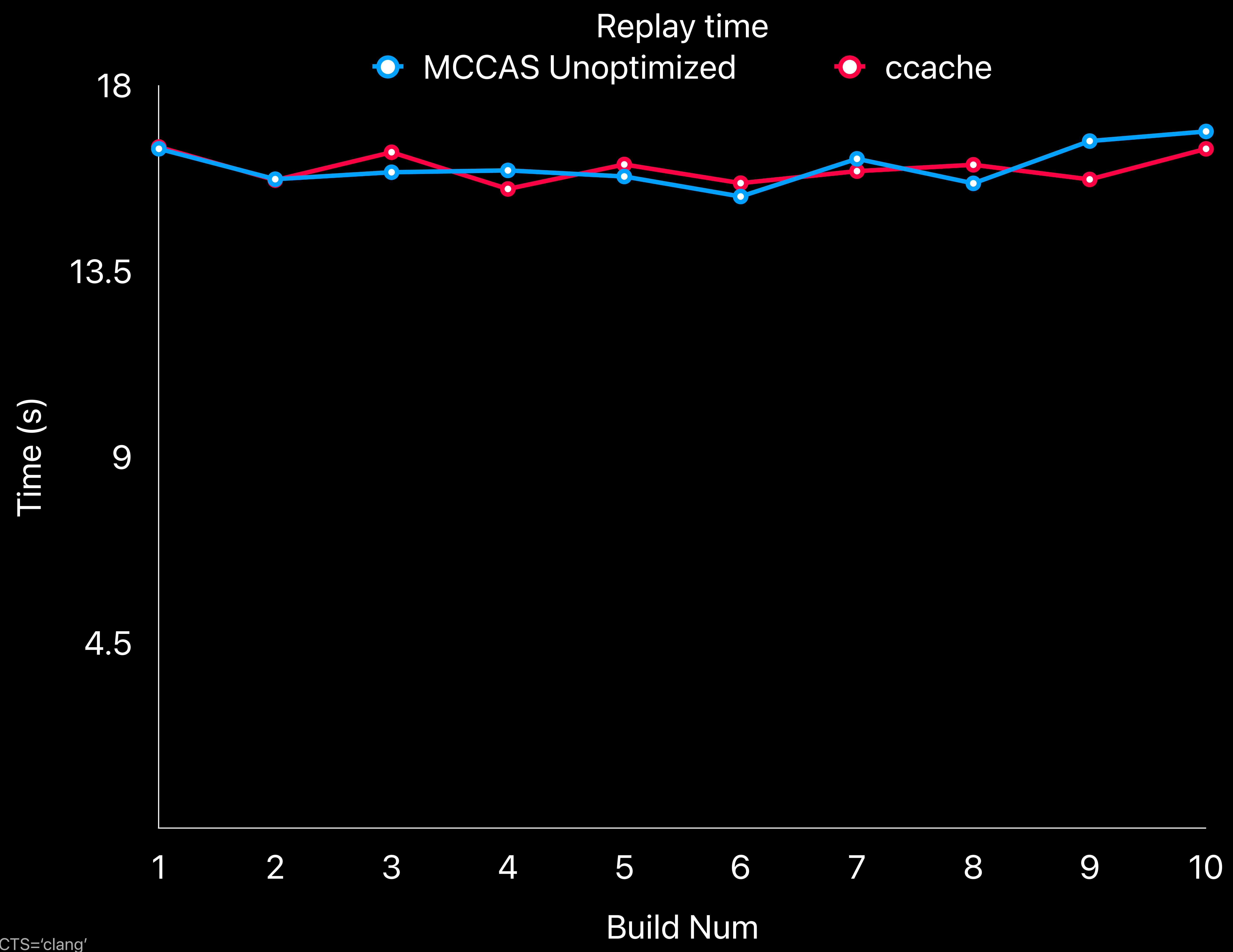
Improvements to replay speed in a MCCAS

- Replay refers to rebuilding a previously cached build

Improvements to replay speed in MCCAS: Results



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Improvements to replay speed in MCCAS

There are two issues with replay speed that we identified

- Materializing the same abbreviations multiple times
- The ULEB decoder was not optimal

Improvements to replay speed in MCCAS

Materializing the same abbreviations multiple times

- Debug abbreviations describe the DIEs in the .debug_info section
- Multiple DIEs can be described by one abbreviation
- Number of abbreviations is always ≤ Number of DIEs

Improvements to replay speed in MCCAS

Materializing the same abbreviations multiple times

- The problem: We were materializing an abbreviation for a DIE every time we wanted to materialize the DIE
- Materialization is expensive, it requires lots of ULEB decoding

Improvements to replay speed in MCCAS

Materializing the same abbreviations multiple times

- Solution: Materialize all abbreviations once, and memoize them
- Cuts down on materialization time for the object file significantly

Improvements to replay speed in MCCAS

The ULEB decoder was not optimal

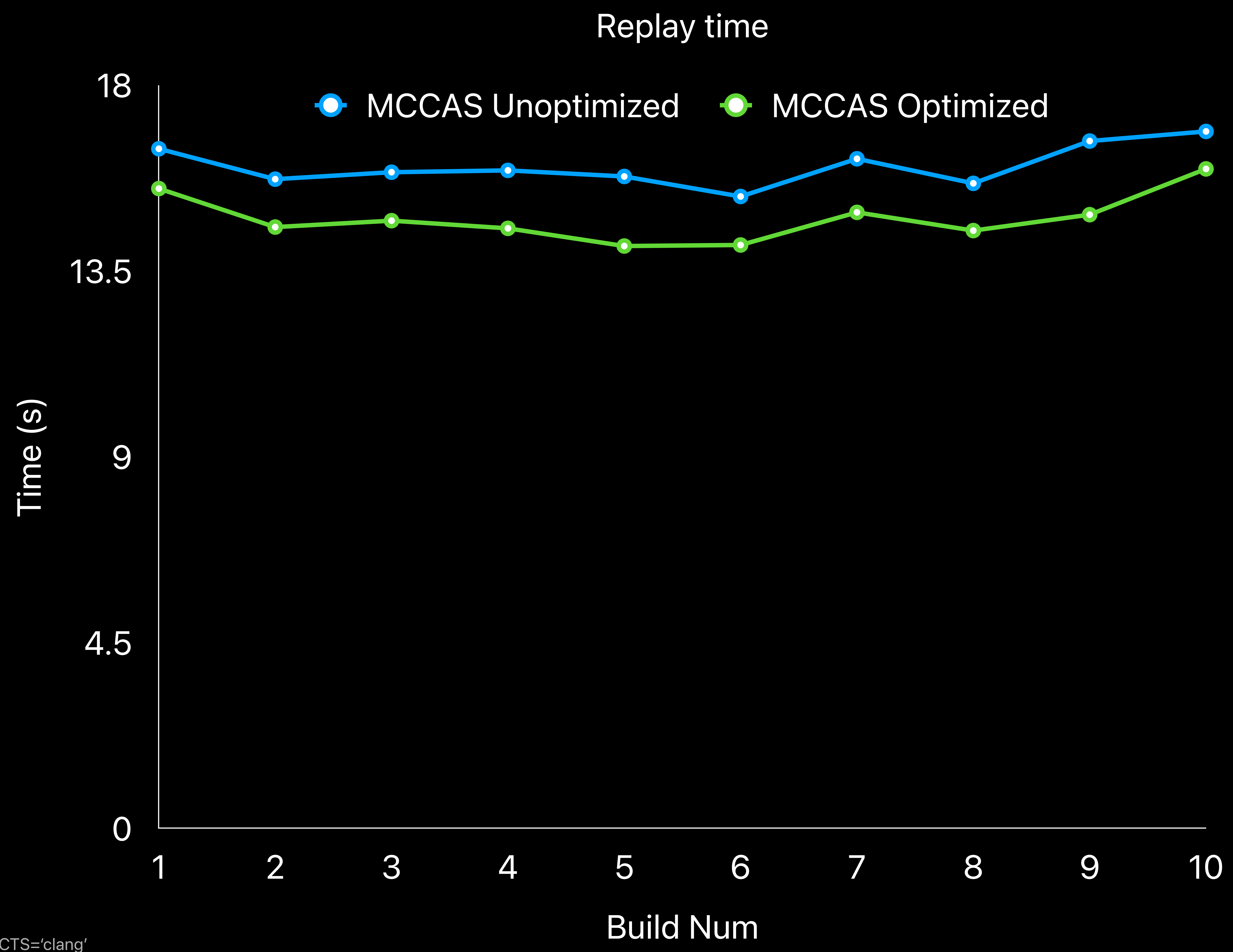
- Materializing any debug info or abbreviations requires ULEB decoding
- The ULEB decoder being used was part of BinaryStreamReader
- BinaryStreamReader is not optimal because it doesn’t guarantee that it’s stream is contiguous
- However, all the CAS Objects that we are reading from, are contiguous

Improvements to replay speed in MCCAS

The ULEB decoder was not optimal

- Solution: Replace BinaryStreamReader with DataExtractor

Improvements to replay speed in MCCAS: Results



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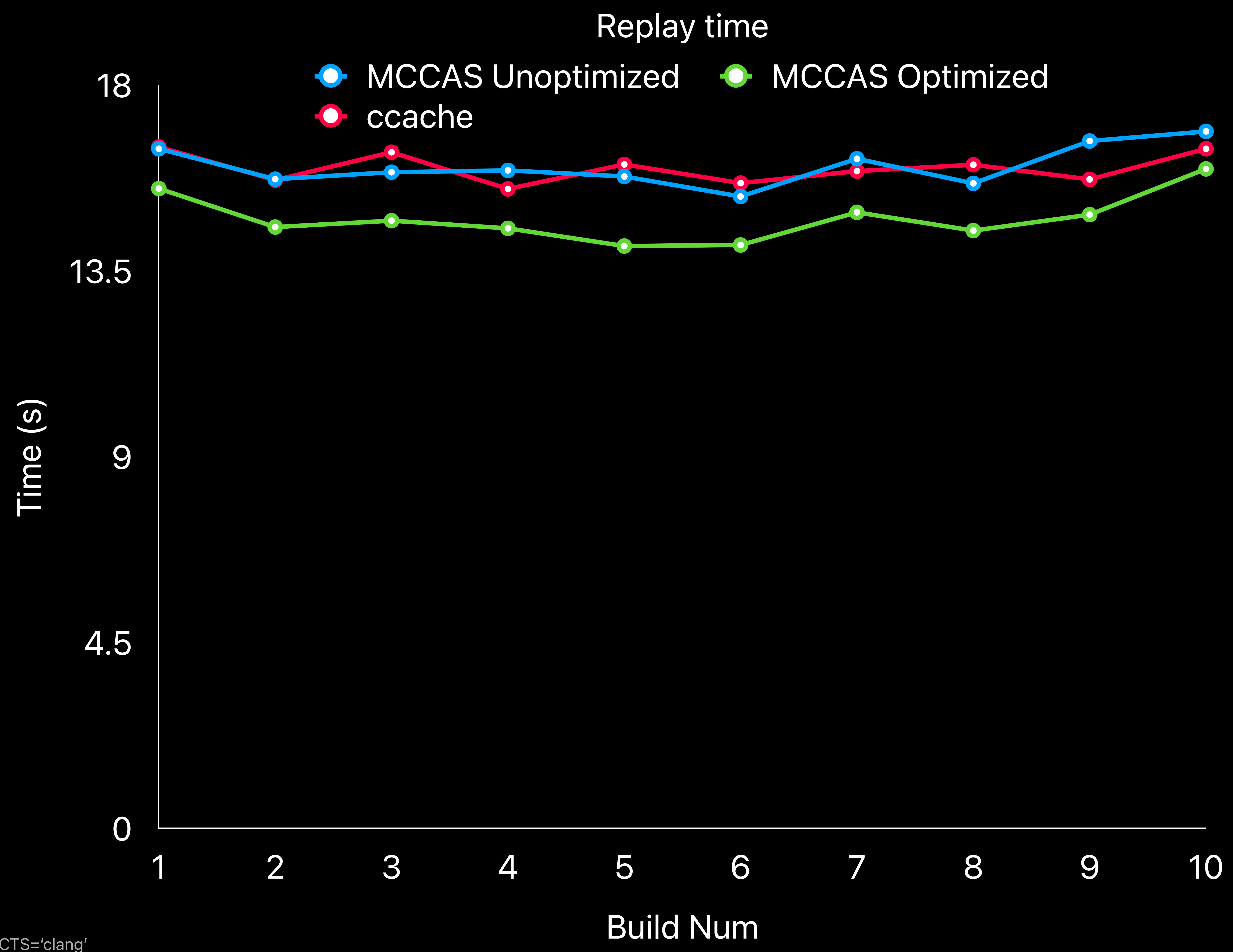
Improvements to replay speed in MCCAS: Results



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MCCAS Support for Swift

- The Swift compiler also supports MCCAS
- Currently, it has been tested with a small open-source project called AlamoFire and works fine
- Further testing is needed to ensure it works correctly

Conclusions

- MCCAS demonstrates a real world use-case for having a CAS-library in LLVM

Conclusions

- MCCAS demonstrates a real world use-case for having a CAS-library in LLVM
- Having a CAS library built into the compiler is advantageous, we can cache clang-modules

LLVM Dev 2023: Caching Explicit Clang Modules with Content-Addressable Storage
https://www.youtube.com/watch?v=6P9787H_SlQ

Future work

- Test and Benchmark MCCAS for Swift
- Implement CAS-specific optimizations for other DWARF sections, such as:
  - `.debug_loc`
  - `.debug_ranges`

Want to contribute?

- llvm-cas initial patch
  - LLVMCAS Implementation: https://github.com/llvm/llvm-project/pull/68448