LLVM Passes

Ettore Speziale

Politecnico di Milano

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What is Available Inside LLVM?

LLVM provides passes performing basic transformations:

- variables promotion
- loops canonicalization
- ...

They can be used to normalize/canonicalize the input:

- transform into a form analyzable for further passes

Input normalization is essential:

- keep passes implementation manageable

LLVM IR is SSA-based:

- every variable is statically assigned exactly once

Statically means that:

- inside each function
- for each variable %foo
- there is only one statement in the form %foo = ...

Static is different from dynamic:

- a static assignment can be executed more than once

Scalar SAXPY

```
float saxpy(float a, float x, float y) {
    return a * x + y;
}
```

Scalar LLVM SAXPY

```
define float @saxpy(float %a, float %x, float %y) {
  %1 = fmul float %a, %x
  %2 = fadd float %1, %y
  ret float %2
}
```

Temporary %1 not reused for %2

Array SAXPY

```
void saxpy(float a, float x[4], float y[4], float z[4]) {
  for(unsigned i = 0; i < 4; ++i)
    z[i] = a * x[i] + y[i];
}
```

Array LLVM SAXPY

```
; <label>:1
  %i.0 = phi i32 [ 0, %0 ], [ %12, %11 ]
  %2 = icmp ult i32 %i.0, 4
  br i1 %2, label %3, label %13
; <label>:3
  ...
  %12 = add i32 %i.0, 1
  br label %1
```

One assignment for loop counter `%i.0`

Max

```
float max(float a, float b) {
  return a > b ? a : b;
}
```

LLVM Max – Bad

```
  %1 = fcmp ogt float %a, %b
  br i1 %1, label %2, label %3
; <label>:2
  %5 = %a
  br label %4
; <label>:3
  %5 = %b
  br label %4
; <label>:4
  ret float %5
```

Why is it bad?

Static Single Assignment

Use **phi** to Avoid Troubles

The %5 variable must be statically set once

LLVM Max

```
  %1 = fcmp ogt float %a, %b
  br i1 %1, label %2, label %3
; <label>:2
  br label %4
; <label>:3
  br label %4
; <label>:4
  %5 = phi float [ %a, %2 ], [ %b, %3 ]
  ret float %5
```

The **phi** instructions is a *conditional move*:

- it takes $(variable_i, label_i)$ pairs
- if coming from predecessor identified by $label_i$, return $variable_i$

Each SSA variable is set only once:

- variable definition

Each SSA variable can be used by multiple instructions:

- variable uses

Algorithms and technical language abuse of these terms:

Let %foo be a variable. If %foo definition has not side-effects, and no uses, dead-code elimination can be efficiently performed by erasing %foo definition from the CFG.

Static Single Assignment
Rationale

Old compilers are not SSA-based:

- putting input into SSA-form is expensive
- cost must be amortized

New compilers are SSA-based:

- SSA easier to work with
- SSA-based analysis/optimizations faster

All modern compilers are SSA-based:

- exception is HotSpot Client compiler

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Canonicalize Pass Input

We will see the following passes:

Useful Passes

Pass	Switch
Variable promotion	`mem2reg`
Loop simplify	`loop-simplify`
Loop-closed SSA	`lcssa`
Induction variable simplification	`indvars`

They are normalization passes:

- put data into a canonical form

Variable Promotion

One of the most difficult things in compiler is:

- considering memory accesses

Plain SAXPY

```
define float @saxpy(float %a, float %x, float %y) {
  %1 = alloca float, align 4
  %2 = alloca float, align 4
  %3 = alloca float, align 4
  store float %a, float* %1, align 4
  store float %x, float* %2, align 4
  store float %y, float* %3, align 4
  %4 = load float* %1, align 4
  %5 = load float* %2, align 4
  %6 = fmul float %4, %5
  %7 = load float* %3, align 4
  %8 = fadd float %6, %7
  ret float %8
}
```

In the SAXPY kernel some **alloca** are generated:

- represent local variables [1]

They are generated due to compiler conservative approach:

- maybe some instruction can take the addresses of such variables, hence a memory location is needed

Complex representations makes hard performing further actions:

- suppose you want to compute `a * x + y` using only one instruction [2]
- hard to detect due to **load** and **store**

[1] Arguments are local variables
[2] FMA4

Variable Promotion

Using Memory Only When Necessary

To limit the number of instruction accessing memory:

- we need to eliminate **load** and **store**
- achieved by promoting variables from memory to registers

Inside LLVM SSA-based representation:

memory Stack allocations – e.g `%1 = alloca float, align 4`

register SSA variables – e.g. `%a`

The `mem2reg` pass focus on:

- eliminating **alloca** with only **load** and **store** uses

Also available as utility:

- `llvm::PromoteMemToReg`

Variable Promotion

Example

Promoting **alloca**

```
%1 = %a
%2 = %x
%3 = %y
%4 = %1
%5 = %2
%6 = fmul %4, %5
%7 = %3
%8 = fadd %6, %7
ret %8
```

After Copy-propagation

```
%1 = fmul %a , %x
%2 = fadd %1, %y
ret %2
```

Starting Point

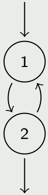
```
%1 = alloca float
%2 = alloca float
%3 = alloca float
store %a , %1
store %x , %2
store %y , %3
%4 = load %1
%5 = load %2
%6 = fmul %4, %5
%7 = load %3
%8 = fadd %6, %7
ret %8
```

Copy propagation performed transparently by the compiler

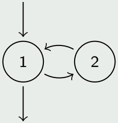
Loops

Different kind of loops:

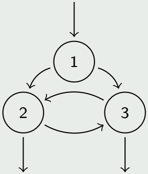
do-while Loops



while Loops



Irreducible Loops



Focus is on one kind of loops:

- natural loops

Natural Loops

A natural loop:

- has only one entry node – *header*
- there is a back edge that enter the loop header

Under this definition:

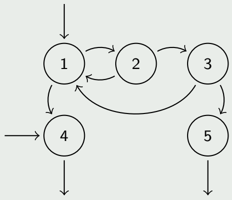
- the irreducible loop is not a natural loop
- since LLVM consider only natural loops, the irreducible loop is not recognize as a loop

Loop Terminology

Loops defined starting from back-edges:

back-edge edge entering loop header: $(3, 1)$

A Loop



header loop entry node: 1

body nodes that can reach back-edge source node – 3 – without passing from back-edge target node – 1 – plus back-edge target node: $\{1, 2, 3\}$

exiting nodes with a successor outside the loop: $\{1, 3\}$

exit nodes with a predecessor inside the loop: $\{4, 5\}$

Loop Simplify

Natural loops allows to identify loops:

- some features are not analysis/optimization friendly

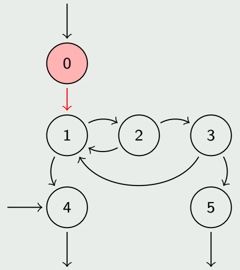
The `loop-simplify` pass normalize natural loops:

pre-header the only predecessor of header node

latch the starting node of the only back-edge

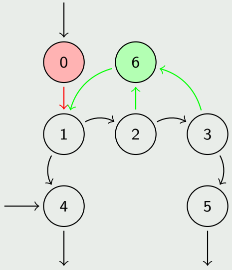
exit-block ensures exits dominated by loop header

Pre-header Insertion

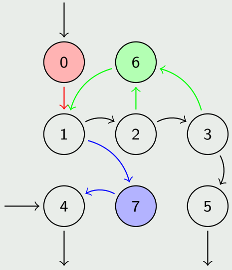


Loop Simplify
Example

Latch Insertion



Exit-block Insertion



- pre-header always executed before entering the loop
- latch always executed before starting a new iteration
- exit-blocks always executed after exiting the loop

Loop-closed SSA

Loop representation can be further normalized:

- `loop-simplify` normalize the shape of the loop
- nothing is said about loop definitions

Keeping SSA form is expensive with loops:

- `lcssa` insert **phi** instruction at loop boundaries for variables defined inside the loop body and used outside
- this guarantee isolation between optimization performed inside and outside the loop
- faster keeping IR into SSA form – propagation of code changes outside the loop blocked by **phi** instructions

Loop-closed SSA
Example

Linear Search

```
unsigned search(float *x, unsigned n, float y) {
  unsigned i, j = 0;
  for(i = 0; i != n; ++i)
    if(x[i] == y)
      j = i;
  return j;
}
```

The example is trivial:

- think about having large loop bodies
- transformation becomes useful

Before LCSSA

```
  %i.0 = phi i32 [ 0, %0 ], [ %10, %9 ]
  %j.0 = phi i32 [ 0, %0 ], [ %j.1, %9 ]
  %2 = icmp ne i32 %i.0, %n
  br i1 %2, label %3, label %11
; <label>:3
  ...
  br i1 %6, label %7, label %8
; <label>:7
  br label %8
; <label>:8
  %j.1 = phi i32 [ %i.0, %7 ], [ %j.0, %3 ]
  br label %9
; <label>:9
  %10 = add i32 %i.0, 1
  br label %1
; <label>:11
  ret i32 %j.0
```

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After LCSSA

```
  %i.0 = phi i32 [ 0, %0 ], [ %10, %9 ]
  %j.0 = phi i32 [ 0, %0 ], [ %j.1, %9 ]
  %2 = icmp ne i32 %i.0, %n
  br i1 %2, label %3, label %11
; <label>:3
  ...
  br i1 %6, label %7, label %8
; <label>:7
  br label %8
; <label>:8
  %j.1 = phi i32 [ %i.0, %7 ], [ %j.0, %3 ]
  br label %9
; <label>:9
  %10 = add i32 %i.0, 1
  br label %1
; <label>:11
  %j.0.lcssa = phi i32 [ %j.0, %1 ]
  ret i32 %j.0.lcssa
```

Induction Variables

Some loop variables are *special*:

- e.g. counters

Generalization lead to induction variables:

- foo is a loop induction variable if its successive values form an arithmetic progression:

$$\text{foo} = \text{bar} * \text{baz} + \text{biz}$$

  where bar, biz are loop-invariant [3], and baz is an induction variable

- foo is a canonical induction variable if it is always incremented by a constant amount:

$$\text{foo} = \text{foo} + \text{biz}$$

  where biz is loop-invariant

[3] Constants inside the loop

Induction Variable Simplification

Canonical induction variables are used to drive loop execution:

- given a loop, the `indvars` pass tries to find its canonical induction variable

With respect to theory, LLVM canonical induction variable is:

- initialized to `0`
- incremented by `1` at each loop iteration

Normalization

Wrap-up

Normalization passes running order:

1. `mem2reg`: limit use of memory, increasing the effectiveness of subsequent passes
2. `loop-simplify`: canonicalize loop shape, lower burden of writing passes
3. `lcssa`: keep effects of subsequent loop optimizations local, limiting overhead of maintaining SSA form
4. `indvars`: normalize induction variables, highlighting the canonical induction variable

Other normalization passes available:

- try running `opt -help`

Contents

Checking Input Properties

Analysis basically allows:

- inspecting input

Keeping analysis information is expensive:

- tuned algorithms updates analysis information when an optimization invalidates them
- incrementally updating analysis is cheaper than recomputing them

Many LLVM analysis supports incremental updates:

- this is an optimization
- forget this feature for the home-work
- focus on information provided by analysis

Useful Analysis

We will see the following passes:

Analysis

Pass	Switch	Transitive
Control flow graph	`none`	No
Dominator tree	`domtree`	No
Post-dominator tree	`postdomtree`	No
Loop information	`loops`	Yes
Scalar evolution	`scalar-evolution`	Yes
Alias analysis	`special`	Yes
Memory dependence	`memdep`	Yes

Requiring analysis by transitivity:

yes llvm :: AnalysisUsage :: addRequiredTransitive<T>()

no llvm :: AnalysisUsage :: addRequired<T>()

Control Flow Graph

The Control Flow Graph is implicitly maintained by LLVM:

- no specific pass to build it

Recap:

- CFG for a function is a set of basic blocks
- a basic block is a set of instructions

Functions and basic blocks acts like containers:

- STL-like accessors: `front()`, `back()`, `size()`, ...
- STL-like iterators: `begin()`, `end()`

Each contained element is aware of its container:

- `getParent()`

Every CFG has an entry basic block:

- the first executed basic block
- it is the root/source of the graph
- get it with llvm::Function::getEntryBlock()

More than one exit blocks can be generated:

- their terminator instructions are **ret**s
- they are the leaves/sinks of the graph
- use llvm::BasicBlock::getTerminator() to get the terminator ...
- ... then check its class

For performance reasons, a custom casting framework is used:

- you cannot use **static_cast** and **dynamic_cast** with types/classes provided by LLVM

LLVM Casting Functions

Meaning	Function
Static cast of Y * to X *	X * llvm :: cast<X>(Y *)
Dynamic cast of Y * to X *	X * llvm :: dyn_cast<X>(Y *)
Is Y an X?	**bool** llvm :: isa<X>(Y *)

Example:

- is BB a sink?

```
llvm::isa<llvm::ReturnInst>(BB.getTerminator())
```

Every basic block BB has one or more:

predecessors from pred_begin(BB) to pred_end(BB)

successors from succ_begin(BB) to succ_end(BB)

Convenience accessors directly available in llvm::BasicBlock:

- e.g. llvm::BasicBlock::getUniquePredecessor()

Other convenience member functions:

- moving a basic block:
  llvm::BasicBlock::moveBefore(llvm::BasicBlock *) or
  llvm::BasicBlock::moveAfter(llvm::BasicBlock *)
- split a basic block:
  llvm::BasicBlock::splitBasicBlock(llvm::BasicBlock::iterator)
- ...

The llvm :: Instruction class define common operations:

- e.g. getting an operand: llvm :: Instruction :: getOperand(**unsigned**)

Subclasses provide specialized accessors:

- e.g the **load** instruction takes an operand that is a pointer: llvm :: LoadInst :: getPointerOperand()

The value produced by the instruction is the instruction itself:

Example

Consider:

%6 = **load** i32* %1, **align** 4

the **load** is described by an instance of llvm :: LoadInst. That instance also models the %6 variable

Instructions

Creating New Instructions

Instructions built using:

- constructors – e.g. `llvm::LoadInst::LoadInst(...)`
- factory methods – e.g. `llvm::GetElementPtrInst::Create(...)`

Interface is not homogeneous:

- some instructions support both methods
- others support only one

At build-time, instructions can be:

- appended to a basic block
- inserted after/before a given instruction

Insertion point usually specified as builder last argument

Side Note
Definitions and Uses

LLVM class hierarchy is built around two simple concepts:

- **value** something that can be used: llvm::Value
- **user** something that can use: llvm::User

A value is a definition:

- llvm::Value::use_begin(), llvm::Value::use_end() to visit uses

An user access definitions:

- llvm::User::op_begin(), llvm::User::op_end() to visit used values

Functions:

- used by call sites
- uses formal parameters

Instructions:

- define an SSA value
- uses operands

Side Note

Value Typing

Every llvm :: Value is typed:

- use llvm :: Value :: getType() to get the type

Since every instructions is/define a value:

- instructions are typed

Example

Consider:

$$\%6 = \textbf{load}\ \text{i32}*\ \%1,\ \textbf{align}\ 4$$

the %6 variable actually is the instruction itself. Its type is the type of **load** return value, i32

Dominance Trees

Dominance trees answer to control-related queries:

- is this basic block executed before that?
- llvm :: DominatorTree

- is this basic block executed after that?
- llvm :: PostDominatorTree

The two trees interface is similar:

- **bool** dominates(X *, X *)
- **bool** properlyDominates(X *, X *)

Where X is an llvm :: BasicBlock or an llvm :: Instruction

Using opt is possible printing them:

- `-view-dom`, `-dot-dom`
- `-view-postdom`, `-dot-postdom`

Loop Information

Loop information are represented using two classes:

- llvm :: LoopInfo analysis detects natural loops
- llvm :: Loop represents a single loop

Using llvm :: LoopInfo it is possible:

- navigate through top-level loops:
  llvm :: LoopInfo :: begin(), llvm :: LoopInfo :: end()
- get the loop for a given basic block:
  llvm :: LoopInfo :: **operator** [](llvm :: BasicBlock ∗)

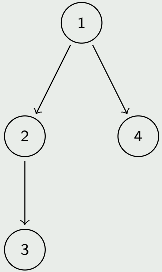
Loops are represented in a nesting tree:

Source

```
while(i < 10) {
  while(j < 10)
    while(k < 10)
      ...

  while(h < 10)
    ...
}
```

Loop Nest



Nest navigation:

- children loops: llvm::Loop::begin(), llvm::Loop::end()
- parent loop: llvm::Loop::getParentLoop()

Loop Information

Query Loops

Accessors for relevant nodes also available:

- **pre-header** llvm::Loop:getLoopPreheader()
- **header** llvm::Loop::getHeader()
- **latch** llvm::Loop::getLoopLatch()
- **exiting** llvm::Loop::getLoopExiting(), llvm::Loop::getExitingBlocks(...)
- **exit** llvm::Loop::getExitBlock() llvm::Loop::getExitBlocks(...)

Loop basic blocks accessible via:

- **iterators** llvm::Loop::block_begin(), llvm::Loop::block_end()
- **vector** std::vector<llvm::BasicBlock *> &llvm::Loop::getBlocks()

Loop Information

Query Loop Instructions

Other llvm::Loop accessors:

- canonical induction variable:
  llvm::Loop::getCanonicalInductionVariable()
- trip count:
  llvm::Loop::getTripCount()

The trip count is a llvm::Value:

- indicates the number of iterations composing the loop
- not always possible computing it

Scalar Evolution

The SCalar EVolution framework:

- represents scalar expressions
- supports recursive updates
- lower burden of explicitly handling expressions composition
- is designed to support general induction variables

Example

```
; <label>:1
  %i.0 = phi [ 0, %0 ], [ %11, %2 ]
  %exitcond = icmp ne %i.0, 10
  br %exitcond, label %2, label %3
; <label>:2
  %11 = add nsw %i.0, 1
  br label %1
```

SCEV for %i.0:

- initial value 0
- incremented
- by 1 at each iteration
- final value 10

Scalar Evolution

Example

Source

```
void foo() {
  int bar[10][20];

  for(int i = 0; i < 10; ++i)
    for(int j = 0; j < 20; ++j)
      bar[i][j] = 0;
}
```

SCEV {A,B,C}<%D>:

- A initial
- B operator
- C operand
- D defining BB

Induction Variables

```
%i.0 = phi i32 [ 0, %0 ], [ %11, %10 ]
--> {0,+,1}<nuw><nsw><%1>                Exits: 10
%j.0 = phi i32 [ 0, %2 ], [ %8, %7 ]
--> {0,+,1}<nuw><nsw><%3>                Exits: 20
```

The scalar evolution framework manages any scalar expression:

Pointer SCEVs

```
%5 = getelementptr %bar, i32 0, i32 %i.0
-->  {%bar,+,80}<nsw><%1>
     Exits: {%bar,+,80}<nsw><%1>
%6 = getelementptr %5, i32 0, i32 %j.0
-->  {{%bar,+,80}<nsw><%1>,+,4}<nsw><%3>
     Exits: {(80 + %bar),+,80}<nw><%1>
```

SCEV is an analysis used for common optimizations:

- induction variable substitution
- strength reduction
- ...

SCEVs are modeled by the `llvm::SCEV` class:

- a subclass for each kind of SCEV: e.g. `llvm::SCEVAddExpr`
- instantiation disabled

A SCEV actually is a tree of SCEVs:

- $\{(80 + \%bar),+,80\} = \{\%1,+,80\}, \%1 = 80 + \%bar$

Tree leaves:

constant `llvm::SCEVConstant`: e.g. 80

unknown [4] `llvm::SCEVUnknown`: e.g. %bar

SCEV tree explorable through the visitor pattern:

- `llvm::SCEVVisitor`

[4] Not further splittable

The llvm :: ScalarEvolution class:

- analyzes SCEVs for a llvm :: Function
- builds SCEVs for values:

  llvm :: ScalarEvolution :: getSCEV(llvm::Value *)
- creates new SCEVs:

  llvm :: ScalarEvolution :: getConstant(llvm :: ConstantInt *)

  llvm :: ScalarEvolution :: getAddExpr(llvm::SCEV *, llvm::SCEV *)

  ...
- gets important SCEVs:

  llvm :: ScalarEvolution :: getBackedgeTakenCount(llvm::Loop *)

  llvm :: ScalarEvolution :: getPointerBase(llvm :: SCEV *)

  ...

Alias Analysis

Let X be an instruction accessing a memory location:

- is there another instruction accessing the same location?

Alias analysis tries to answer the question:

application memory operation scheduling

problem often fails

Different algorithms for alias analysis:

- common interface – `llvm::AliasAnalysis` – for all algorithms
- by default, basic alias analyzer – `basicaa` – is used

Requiring Alias Analysis

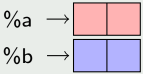
```
AU.addRequiredTransitive<llvm::AliasAnalysis>();
```

Alias Analysis
Memory Representation

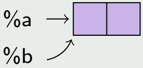
Source

```
%1 = load i16* %a
%2 = load i16* %b
 store i16 %2, i32* %a
 store i16 %1, i32* %b
```

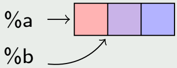
Distinct Locations



Same Location



Overlapping Locations



Basic building block is llvm :: AliasAnalysis :: Location:

- address: e.g. %a
- size: e.g. 2 bytes

Alias Analyzer
Basic Interface

Given two locations X, Y, the alias analyzer classifies them:

- llvm :: AliasAnalyzer :: NoAlias: X and Y are different memory locations
- llvm :: AliasAnalyzer :: MustAlias: X and Y are equal – i.e. they points to the same address
- llvm :: AliasAnalyzer :: PartialAlias : X and Y partially overlap – i.e. they points to different addresses, but the pointed memory areas partially overlap
- llvm :: AliasAnalyzer :: MayAlias: unable to compute aliasing information – i.e. X and Y can be different locations, or X can be a complete/partial alias of Y

Queries performed using:

- llvm :: AliasAnalyzer :: alias (X, Y)

Alias Analyzer
Mid-level Interface

Basic alias analyzer interface is low-level – we would like expressing queries about a single pointer X:

- how referenced memory location is accessed?
- which other instructions reference the same location?

What we need is a set, to classify memory locations:

- construct a `llvm::AliasSetTracker` starting from a `llvm::AliasAnalyer *`
- it builds `llvm::AliasSet`s

For a given location X, a `llvm::AliasSet`:

- contains all locations aliasing with X

Each alias set references the memory:

- llvm :: AliasSet :: NoModRef: no memory reference – i.e. the set is empty
- llvm :: AliasSet :: Mod: memory accessed in write-mode – e.g. a **store** is inside the set
- llvm :: AliasSet :: Ref: memory accessed in read-mode – e.g. a **load** is inside the set
- llvm :: AliasSet :: ModRef: memory accessed in read-write mode – e.g. a **load** and a **store** inside the set

Entry point is llvm::AliasSetTracker::getAliasSetForPointer(...):

- llvm::Value *: location address
- uint64_t: location size
- llvm::MDNode *: used for type-based alias analysis [5]
- **bool** *: whether a new llvm::AliasSet has been created to hold the location – location does not alias up to now

Having the llvm::AliasSet:

- STL container-like interface: size(), begin(), end(), ...
- check reference type: llvm::AliasSet::isRef(), ...
- check aliasing type: llvm::AliasSet::isMustAlias(), ...

[5] set to NULL

The llvm :: MemoryDependenceAnalysis wraps alias analysis to answer queries in the following form:

- let %foo be an instruction accessing memory. Which preceding instructions does %foo depends on?

Reads:

- **store**s writing memory locations aliases with the one references by %foo

Writes:

- **load**s reading memory locations aliased with the one referenced by %foo

Memory Dependence Analysis

APIs

Let %foo be a llvm :: Instruction accessing memory:

- call llvm :: MemoryDependenceAnalysis::getDependency(...)
- you get a llvm :: MemDepResult

Dependencies are classified:

- llvm :: MemDepResult::isClobber(): an instruction clobbering – i.e. potentially modifying – location referenced by %foo has been found
- llvm :: MemDepResult::isDef(): an instruction defining – e.g. writing – the exact location referenced by %foo has been found
- llvm :: MemDepResult::isNonLocal(): no dependency found on %foo basic block
- llvm :: MemDepResult::isNonFuncLocal(): no dependency found on %foo function

Contents

Conclusions

Inside LLVM there a lot of passes:

normalization put program into a canonical form

analysis get info about program

Please remember that

- a good compiler writer re-uses code
- check LLVM sources before re-implementing a pass

Contents

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