Compilation and optimization with security annotations

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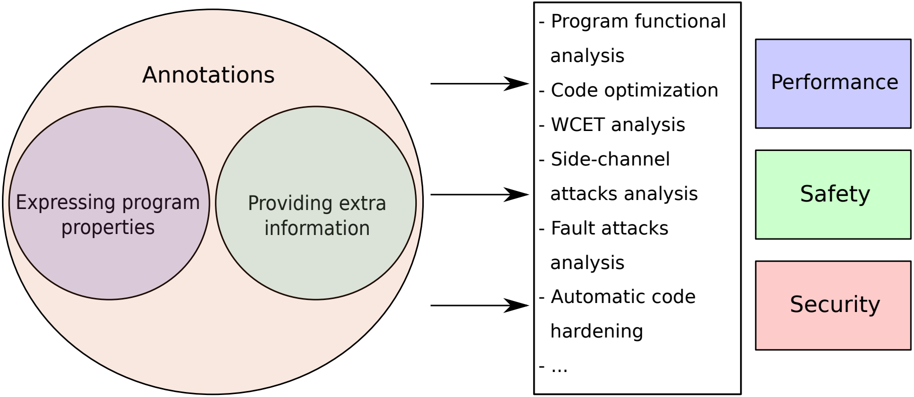
Outline

1. Introduction
2. Proposed solutions
3. Conclusion
4. References

Background and motivation

- *Annotations = program properties + extra information*
- Applied to security, safety, real-time, optimization



- Annotations are consumed by program analysis or transformation
- Source level to binary level

Related work

- Annotation languages
  - GNU attributes, Microsoft's SAL, JML for Java, ACSL for C, etc.
  - At source-level

⇒ No annotation language covers the wide range of security properties

- Other usages than specifying program behaviors
  - Augment compiler optimizations [NZ13]
  - Automatic code hardening at compilation time [Hil14]
  - Flow information for Worst-Case Execution Time (WCET) analysis at binary level [SCG$^+$18]

⇒ No compiler propagating annotations until the binary other than WCET-aware compilers

Examples of properties: authentication code [DPP+16]

```
int verifyPIN(char *cardPin, char *userPin, int *cnt) {
  int i;
  int diff;
  if (*cnt > 0) {
    diff = 0;

    // Comparison loop
    for (i = 0; i < PIN_SIZE; i++)
      if (userPin[i] != cardPin[i])
        diff = 1;

    // Loop protection against fault attacks
    if (i != PIN_SIZE)
      return BOOL_FALSE;

    if (diff == 0) {
      // PIN codes match
      *cnt = MAX_ATTEMPT;
      return BOOL_TRUE;
    } else {
      // PIN codes differ
      (*cnt)--;
      return BOOL_FALSE;
    }
  }
  return BOOL_FALSE;
}
```

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      // PIN codes differ
      (*cnt)--;
      return BOOL_FALSE;
    }
  }
  return BOOL_FALSE;
}
```

Functional property:

- `verifyPIN` returns `BOOL_TRUE` only when PIN codes match

Examples of properties: authentication code [DPP+16]

```
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  return BOOL_FALSE;
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```

Non-functional property:

- Card PIN code must be kept secret

Examples of properties: authentication code [DPP+16]

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int verifyPIN(char *cardPin, char *userPin, int *cnt) {
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  if (*cnt > 0) {
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    for (i = 0; i < PIN_SIZE; i++)
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      // PIN codes differ
      (*cnt)--;
      return BOOL_FALSE;
    }
  }
  return BOOL_FALSE;
}
```

Non-functional property:

- Comparison loop must be executed exactly `PIN_SIZE` times

Examples of properties: authentication code [DPP+16]

```
int verifyPIN(char *cardPin, char *userPin, int *cnt) {
  int i;
  int diff;
  if (*cnt > 0) {
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      // PIN codes differ
      (*cnt)--;
      return BOOL_FALSE;
    }
  }
  return BOOL_FALSE;
}
```
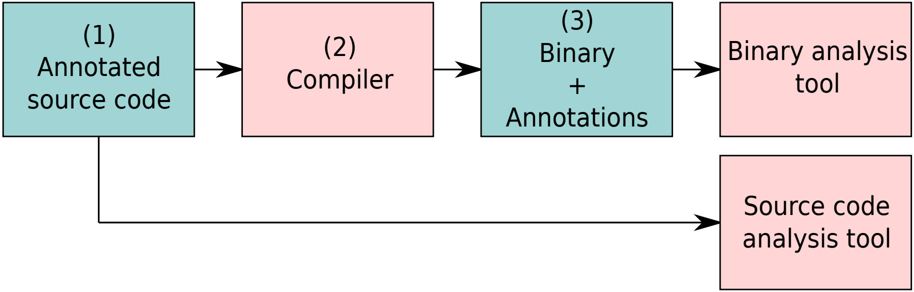

Non-functional property:

- Loop protection should not be removed by compiler optimizations

Problem statement



1. A source-level annotation language to express a wide range of properties
2. An annotation-aware, optimizing, LLVM-based compilation framework which consumes/produces/propagates annotations
3. A binary-level representation for the source-level annotation language

Outline

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2. Proposed solutions
   - Source-level annotation language
   - Binary-level representation of the annotation language
   - Annotations in LLVM: representation and propagation
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Annotation language by example: functional properties

ACSL already allows specifying program functional properties

- `verifyPIN` returns `BOOL_TRUE` only when PIN codes match

```
#define ANNOT(s) __attribute__((annotate(s)))

// Function annotation
ANNOT("\\ensures \\result == BOOL_TRUE &&"
               " \\forall i; 0 <= i < PIN_SIZE: userPin[i] == cardPin[i];"
      "\\ensures \\result == BOOL_FALSE &&"
               " \\exists i; 0 <= i < PIN_SIZE: userPin[i] != cardPin[i];")
int verifyPIN(char *cardPin, char *userPin, int *cnt) {
  ...
}
```

Annotation language by example: non-functional properties

Introduce *semantic predicates* to specify non-functional properties

- Card PIN code must be kept secret

```
#define ANNOT(s) __attribute__((annotate(s)))

// Variable annotation
int verifyPIN(ANNOT("\\invariant \\secret()") char *cardPin,
                                               char *userPin,
                                               int *cnt) {
  ...
}
```

Annotation language by example: non-functional properties

Introduce *semantic predicates* to specify non-functional properties

- Loop protection does not get removed

```
#define ANNOT(s) __attribute__((annotate(s)))

int verifyPIN(char *cardPin, char *userPin, int *cnt) {
  int i;
  int diff;
  if (*cnt > 0) {
    diff = 0;

    for (i = 0; i < PIN_SIZE; i++)
      if (userPin[i] != cardPin[i])
        diff = 1;

    // Statement annotation
    prop1: ANNOT("\\ensures \\sensitive();")
    if (i != PIN_SIZE)
      return BOOL_FALSE;

    if (diff == 0) {
      *cnt = MAX_ATTEMPT;
      return BOOL_TRUE;
    } else {
      (*cnt)--;
      return BOOL_FALSE;
    }
  }
  return BOOL_FALSE;
}
```

Annotation language by example: side-effect properties

Introduce *semantic variables* to capture side-effects of the code

- Comparison loop must be executed exactly `PIN_SIZE` times

```
#define ANNOT(s) __attribute__((annotate(s)))

int verifyPIN(char *cardPin, char *userPin, int *cnt) {
  int i;
  int diff;
  if (*cnt > 0) {
    diff = 0;

    // Statement annotation
    prop1: ANNOT("\\ensures \\count() == PIN_SIZE;")
    for (i = 0; i < PIN_SIZE; i++)
      if (userPin[i] != cardPin[i])
        diff = 1;

    if (i != PIN_SIZE)
      return BOOL_FALSE;

    if (diff == 0) {
      *cnt = MAX_ATTEMPT;
      return BOOL_TRUE;
    } else {
      (*cnt)--;
      return BOOL_FALSE;
    }
  }
  return BOOL_FALSE;
}
```

Annotation language summary

- $Annotation = Annotated\ Entity \wedge Predicate \wedge Predicate\ Variables$
- $Annotated\ Entity = Function \vee Variable \vee Statement$
- $Predicate = Logic\ Predicate \vee Semantic\ Predicate$
- $Predicate\ Variable = Variable\ Referenced\ in\ Predicate$

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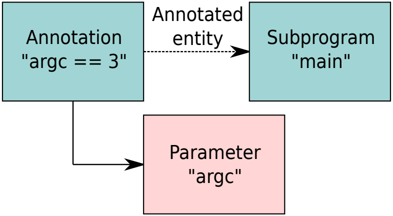
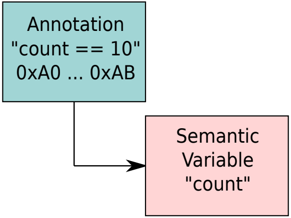
Extending DWARF debugging format

- Executable program = tree of *Debugging Information Entries* (DIEs)
- DIE = tag + attribute(s) + child DIEs (if any)
- Introduce new tags and attributes to represent annotations and semantic variables



Function annotation



Statement annotation

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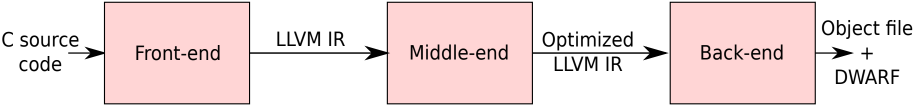
Annotation representation in LLVM



C source code

Front-end

LLVM IR

Middle-end

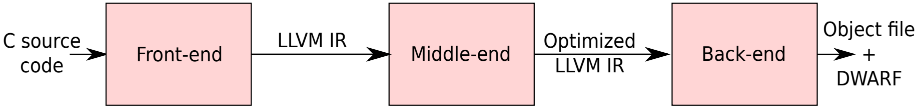
Optimized LLVM IR

Back-end

Object file + DWARF

- Existing metadata mechanism to convey extra information about the code
- Debug info: only metadata preserved and emitted into the binary
  ⇒ used to represent function and variable annotations

Annotation representation in LLVM

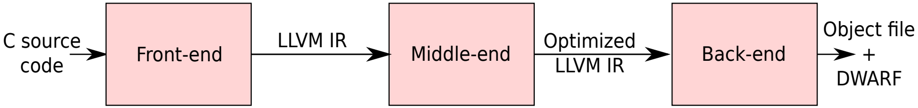


- Existing metadata mechanism to convey extra information about the code

- Debug info: only metadata preserved and emitted into the binary
  ⇒ used to represent function and variable annotations

- Debug info: does have representation for source statements, but too painful to maintain
  ⇒ annotation markers (≈ memory fences) to delimit the region corresponding to an annotated statement

Annotation representation in LLVM



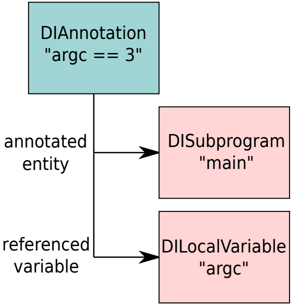
C source code → Front-end → LLVM IR → Middle-end → Optimized LLVM IR → Back-end → Object file + DWARF

- Existing metadata mechanism to convey extra information about the code
- Debug info: only metadata preserved and emitted into the binary
  ⇒ used to represent function and variable annotations
- Debug info: does have representation for source statements, but too painful to maintain
  ⇒ annotation markers (≈ memory fences) to delimit the region corresponding to an annotated statement
  ⇒ inspired by lifetime markers: all instructions from a start marker to a corresponding end marker are annotated

Annotation representation in LLVM: function and variable

Function + variable annotation metadata

- predicate
- reference to debug info metadata for the annotated entity
- reference to debug info metadata for the predicate variables (if any)



DIAnnotation "argc == 3"

annotated entity

DISubprogram "main"

referenced variable

DILocalVariable "argc"

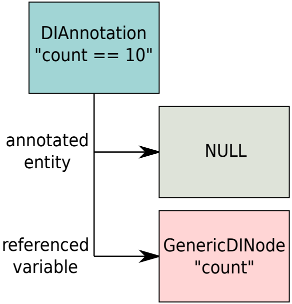
- Emitted by `clang`
- Propagated and emitted to the binary using the same mechanism as debug info metadata

Annotation representation in LLVM: statement

Statement annotation metadata

- predicate
- reference to debug info metadata for the predicate variables (if any)

- Emitted by `clang`
- Propagated and emitted to the binary using the same mechanism as debug info metadata



DIAnnotation "count == 10"

annotated entity

NULL

referenced variable

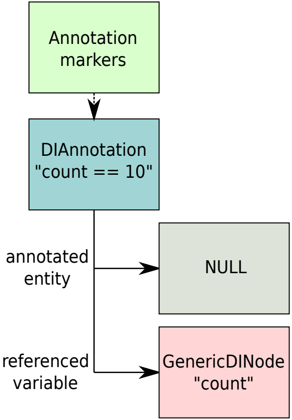
GenericDINode "count"

Annotation representation in LLVM: statement

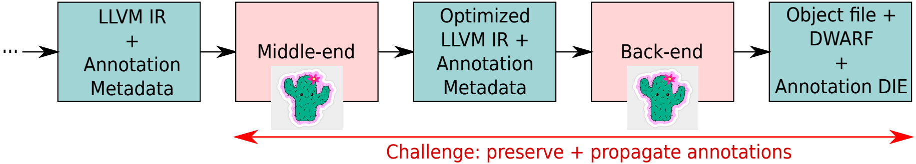
Statement annotation metadata

- predicate
- reference to debug info metadata for the predicate variables (if any)

- Emitted by `clang`
- Propagated and emitted to the binary using the same mechanism as debug info metadata
- Embedded in the annotation markers



Annotation propagation in LLVM: challenge


...

LLVM IR + Annotation Metadata

Middle-end

Optimized LLVM IR + Annotation Metadata

Back-end

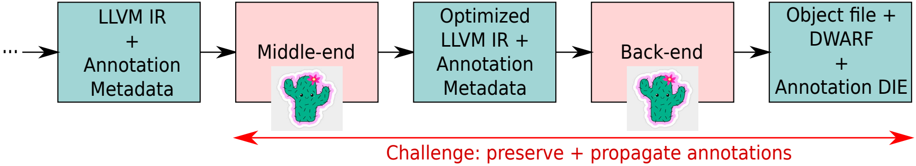
Object file + DWARF + Annotation DIE

Challenge: preserve + propagate annotations

Goal: preserving

1. the annotated entity
2. the predicate variables
3. the annotation metadata itself

Annotation propagation in LLVM: challenge



Goal: preserving

1. the annotated entity
   ⇒ maintain correct debug info for variable and function annotations
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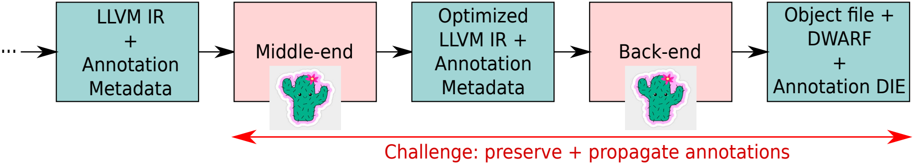
3. the annotation metadata itself

Annotation propagation in LLVM: challenge



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   ⇒ maintain correct annotated region for statement annotations
2. the predicate variables
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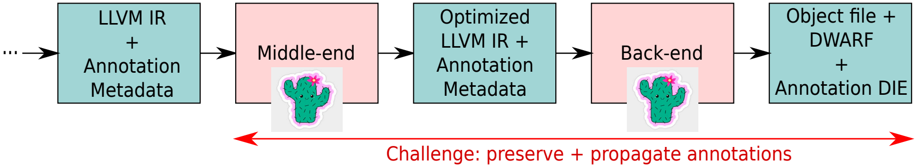
Annotation propagation in LLVM: challenge



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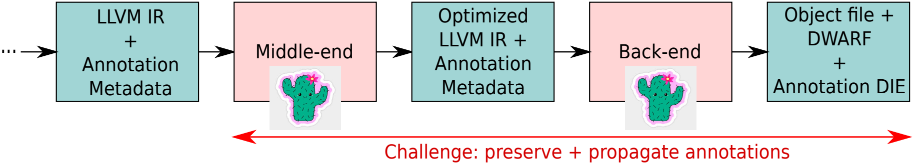
   ⇒ maintain correct debug info for these variables

3. the annotation metadata itself

Annotation propagation in LLVM: challenge



Goal: preserving

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   ⇒ maintain correct annotated region for statement annotations

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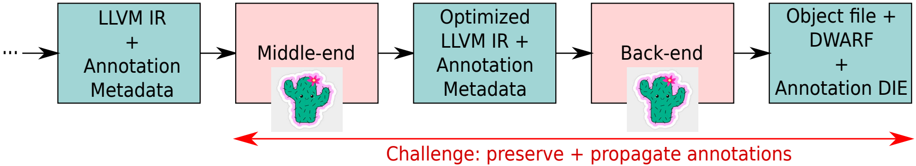
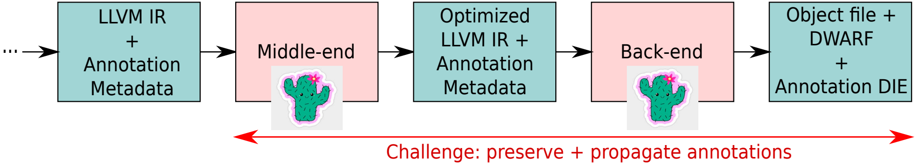
3. the annotation metadata itself
   ⇒ annotation metadata is kept aside from the code and does not interact with optimizations

Annotation propagation in LLVM: problems



Two different types of problems:

Annotation propagation in LLVM: problems



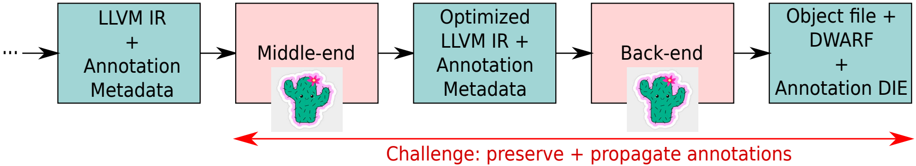
... → LLVM IR + Annotation Metadata → Middle-end → Optimized LLVM IR + Annotation Metadata → Back-end → Object file + DWARF + Annotation DIE

Challenge: preserve + propagate annotations

Two different types of problems:

1. Debug info propagation
   - Maintaining debug info = best-effort, no guarantee
   - Implementation bugs
   - Our biggest hurdle: correct location ranges for auto variables

Annotation propagation in LLVM: problems



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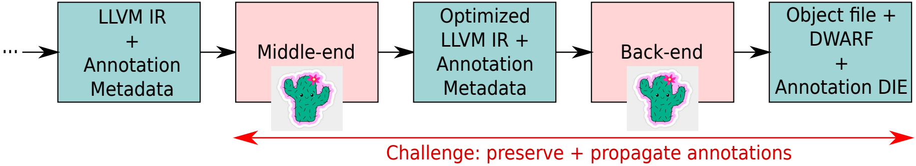


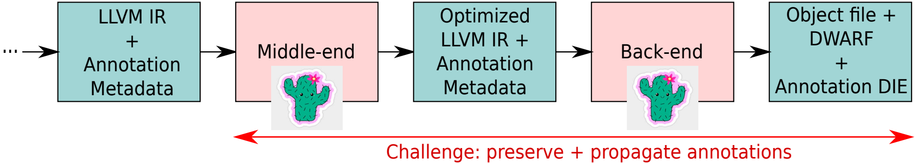
Two different types of problems:

1. Debug info propagation
    - Maintaining debug info = best-effort, no guarantee
    - Implementation bugs
    - Our biggest hurdle: correct location ranges for auto variables

      ⇒ analysis on the generated binary to recover the information

      ⇒ assume that debug info is correct for now

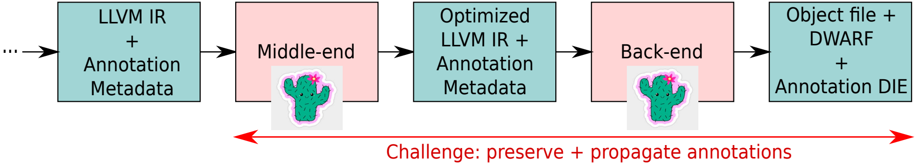
Annotation propagation in LLVM: problems



Two different types of problems:

1. Debug info propagation
2. Statement annotation propagation
    - Annotated instructions removed
    - Annotated instructions merged with not annotated ones, or with ones annotated with a different annotation

Annotation propagation in LLVM: problems



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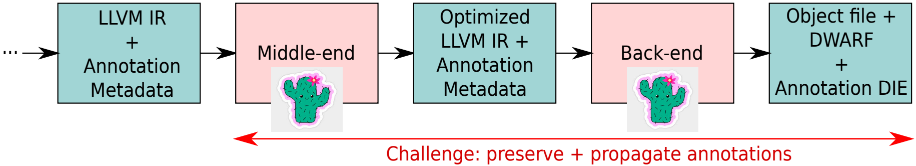
⇒ How to preserve an annotated region?

Annotation propagation in LLVM: problems



Challenge: preserve + propagate annotations

Two different types of problems:

1. Debug info propagation
2. Statement annotation propagation
   - Annotated instructions removed
   - Annotated instructions merged with not annotated ones, or with ones annotated with a different annotation

⇒ How to preserve an annotated region?

⇒ What does "preserving an annotated region" even mean?

Statement annotation propagation in LLVM: correctness

An annotated region is preserved

1. Isolation conditions (can be relaxed, depending on the annotation's nature)
2. Optimization conditions for the annotated region

Statement annotation propagation in LLVM: correctness

An annotated region is preserved

1. Isolation conditions (can be relaxed, depending on the annotation's nature)
    - no external instructions should get into the region
    - no annotated instructions should get out of the region

Statement annotation propagation in LLVM: correctness

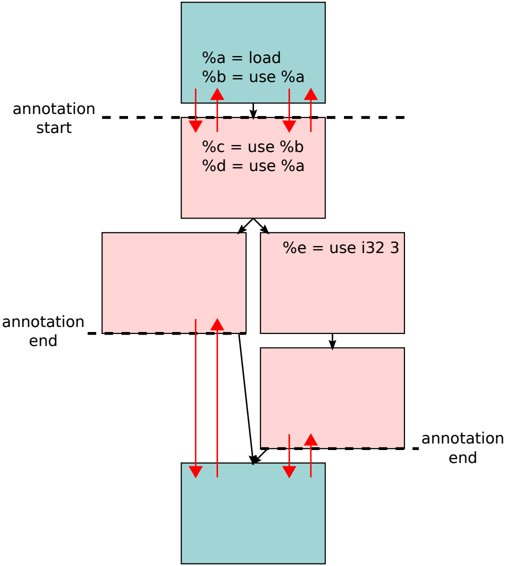
An annotated region is preserved

1. Isolation conditions (can be relaxed, depending on the annotation's nature)
    - no external instructions should get into the region
    - no annotated instructions should get out of the region

   ⇒ annotation markers only guarantee for memory accesses and instructions with side-effects

   What about constants, registers, instructions without side-effects?

Statement annotation propagation in LLVM: SSA barriers

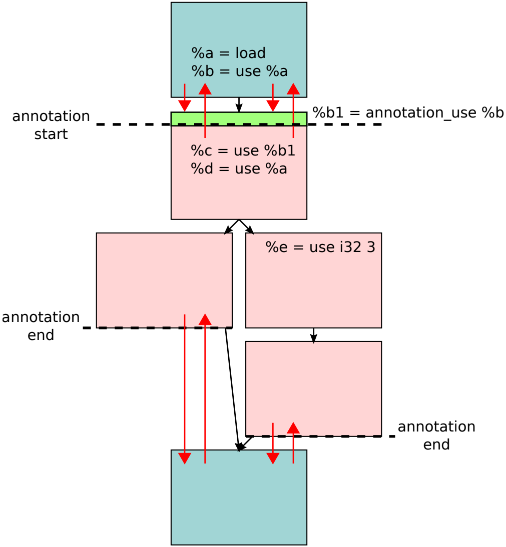


```
%a = load
%b = use %a
```

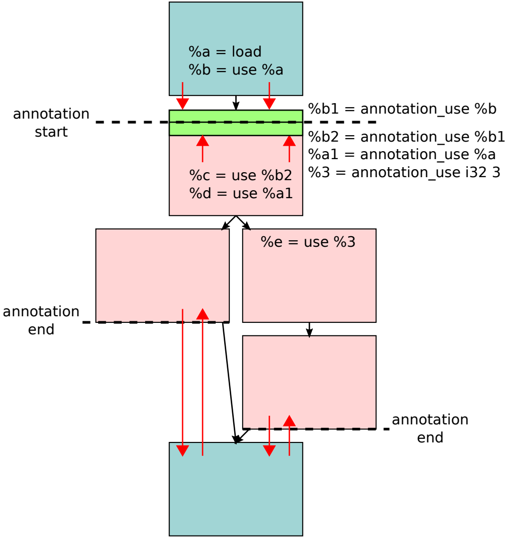
```
%c = use %b
%d = use %a
```

```
%e = use i32 3
```

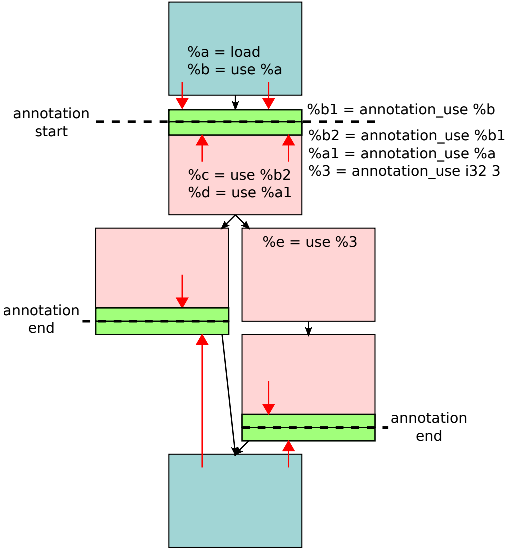
Statement annotation propagation in LLVM: SSA barriers



Statement annotation propagation in LLVM: SSA barriers

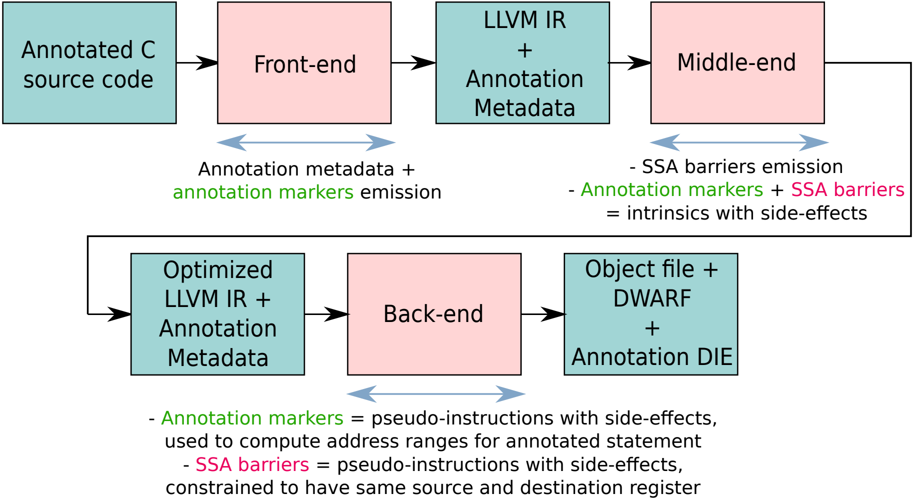


Statement annotation propagation in LLVM: SSA barriers



Annotation propagation in LLVM: complete flow

Current implementation



Annotated C source code

Front-end

LLVM IR + Annotation Metadata

Middle-end

Optimized LLVM IR + Annotation Metadata

Back-end

Object file + DWARF + Annotation DIE

Annotation metadata + annotation markers emission

- SSA barriers emission
- Annotation markers + SSA barriers = intrinsics with side-effects

- Annotation markers = pseudo-instructions with side-effects, used to compute address ranges for annotated statement
- SSA barriers = pseudo-instructions with side-effects, constrained to have same source and destination register

Statement annotation propagation in LLVM: correctness

An annotated region is preserved

1. Isolation conditions (can be relaxed, depending on the annotation's nature)
   ⇒ guaranteed by annotation markers + SSA barriers

Statement annotation propagation in LLVM: correctness

An annotated region is preserved

1. Isolation conditions (can be relaxed, depending on the annotation's nature)
   ⇒ guaranteed by annotation markers + SSA barriers
2. Optimizations of the annotated region
   - Default to the same level as other regions

Statement annotation propagation in LLVM: correctness

An annotated region is preserved

1. Isolation conditions (can be relaxed, depending on the annotation's nature)

   ⇒ guaranteed by annotation markers + SSA barriers

2. Optimizations of the annotated region
   - Default to the same level as other regions
   - Can be controlled by additional, annotation-specific constraints on the optimizations allowed within the annotated region

Statement annotation propagation in LLVM: correctness

An annotated region is preserved

1. Isolation conditions (can be relaxed, depending on the annotation's nature)

   ⇒ guaranteed by annotation markers + SSA barriers

2. Optimizations of the annotated region
   - Default to the same level as other regions
   - Can be controlled by additional, annotation-specific constraints on the optimizations allowed within the annotated region
     - no optimization

Statement annotation propagation in LLVM: correctness

An annotated region is preserved

1. Isolation conditions (can be relaxed, depending on the annotation's nature)
   $\Rightarrow$ guaranteed by annotation markers + SSA barriers

2. Optimizations of the annotated region
   - Default to the same level as other regions
   - Can be controlled by additional, annotation-specific constraints on the optimizations allowed within the annotated region
     - no optimization

     - less optimizing than the default level

Statement annotation propagation in LLVM: correctness

An annotated region is preserved

1. Isolation conditions (can be relaxed, depending on the annotation's nature)
   ⇒ guaranteed by annotation markers + SSA barriers
2. Optimizations of the annotated region
   - Default to the same level as other regions
   - Can be controlled by additional, annotation-specific constraints on the optimizations allowed within the annotated region
     - no optimization
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     - less optimizing than the default level

Statement annotation propagation in LLVM: correctness

An annotated region is preserved

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⇒ ideal solution: per-region optimization mechanism

Validation: methodology

1. Annotating the source code
2. Compiling at LLVM *-O2*
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- DWARF section
  - Correct annotation DIE
  - Correct debug info for annotated function or variable
  - Correct debug info for predicate variables
- `.text` section: code generated for the annotated statement (respecting isolation + optimization conditions)

Validation: benchmarks and results

- Applications tested + annotations considered
  - VerifyPIN without protection: function behavior
  - VerifyPIN + Control Flow Integrity protection [LHB14]: protection
  - VerifyPIN + loop protection [Wit]: protection
  - First-order masked AES [HOM06]: secret + masked variables
  - RSA [DPP$^+$16]: random functions and variables
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- Results
  - annotations found in DWARF section
  - BUT auto variable location ranges might be erroneous

    ⇒ patch submitted to fix the bug
  - protections preserved in machine code

Validation: preserving the protection

- Protection inserted at source level might be removed by optimizations
- Traditionally, 2 solutions to preserve the protections:
    - Compiling without optimization (`-O0`)
    - Using fragile programming tricks (e.g. `volatile`)
- Preliminary comparison: simulated for ARM Cortex-M3

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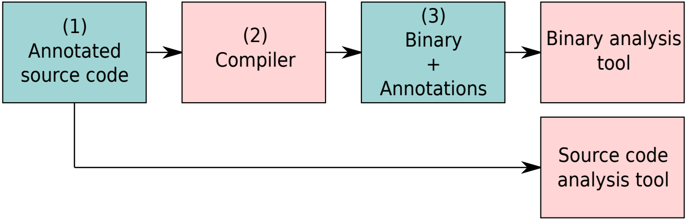
	VerifyPIN + loop protection		VerifyPIN + CFI protection	
	Protection	Exec. instr.	Protection	Exec. instr.
O0	✓	126	✓	1299
O2 + `volatile`	✓	89	✓	890
O2 + annotation	✓	62	✓	629
O2	✗	24	✗	130

- SSA barriers preserve the protections and region isolation while enabling heavy optimizations (`-O2`)

Outline

1. Introduction
2. Proposed solutions
3. Conclusion
4. References

Conclusion



1. ACSL-based source-level annotation language for wide range of properties
2. Mechanisms towards annotation-aware compilation framework
3. DWARF extension for binary-level annotation representation

Perspectives

- Evaluation of the annotation propagation impact on the compiler and the generated executable performance
- Automatic process to validate *annotation correctness*
- Per-region fine-grained optimization control

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- Evaluation of the annotation propagation impact on the compiler and the generated executable performance
- Automatic process to validate *annotation correctness*
- Per-region fine-grained optimization control
- PhD graduation

Outline

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