Branch Coverage: Squeezing more out of LLVM Source-based Code Coverage

Alan Phipps, Texas Instruments

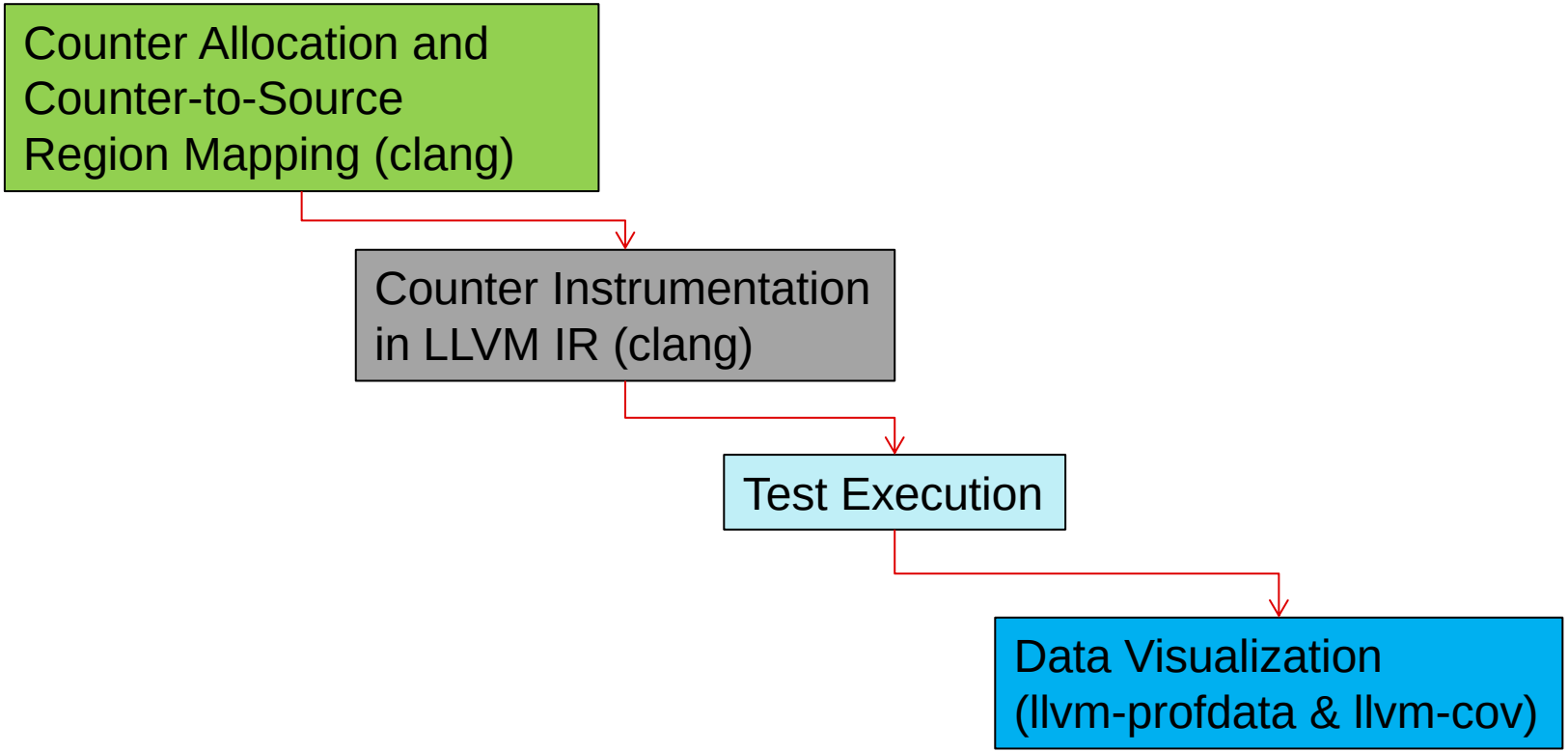
2020 LLVM Developers' Meeting

What is Source-based Code Coverage?

- A measurement for how thoroughly code has been executed during testing
  - Ideally all sections of code have an associated test
  - Un-executed code may be at higher risk of having lurking bugs

- Supported Coverage criteria (in increasing level of granularity)
  - **Function**
    - Percentage of code functions executed at least once
  - **Line**
    - Percentage of code lines executed at least once
  - **Region**
    - Percentage of code statements executed at least once

Basic Phases (High Level)



Counter Region Mapping and Instrumentation

- Counters are inserted into basic blocks of generated code mapped to source

```
line  9: bool foo(int x, int y) {
           Counter1++
line 10:   if ((x > 0) && (y > 0))
                                ^Counter2++
             Counter3++
line 11:     return true;
line 12:
line 13:   return false;
line 14: }
```

- **Counter1** instrumented to track
  - Region (9:24 → 10:23)
  - Function (line 9 – `foo()`)
  - Line (line 10)
  - Statement: if-stmt
- **Counter2** instrumented to track
  - Region (10:18 → 10:25)
  - Statement (y > 0)
- **Counter3** instrumented to track
  - Region (11:0 → 11:12)
  - Line coverage (line 11)
- **(Counter1 – Counter3)** tracks
  - Region (12:0 → 14:0)
  - Line coverage (line 13)

LLVM Coverage Visualization

- LLVM Coverage Utility (llvm-cov)

Line	Count	Source (jump to first uncovered line)
8		
9	2	bool foo (int x, int y) {
10	2	if ((x > 0) && (y > 0))
11	0	return true;
12	2	
13	2	return false;
14	2	}

- Text (llvm-cov)

```
  8|       |
  9|      2|bool foo (int x, int y) {
 10|      2|  if ((x > 0) && (y > 0))
                              ^1
 11|      0|    return true;
 12|      2|
 13|      2|  return false;
 14|      2|}
```

Coverage Report

Created: 2020-09-09 15:28

Click here for information about interpreting this report.

Filename	Function Coverage	Line Coverage	Region Coverage
scratch/aphipps/llvmtest/cov/demo/brdemo.cc	100.00% (2/2)	96.15% (25/26)	90.00% (9/10)
Totals	100.00% (2/2)	96.15% (25/26)	90.00% (9/10)

Generated by llvm-cov -- llvm version 12.0.0git

Why is branch Coverage Important?

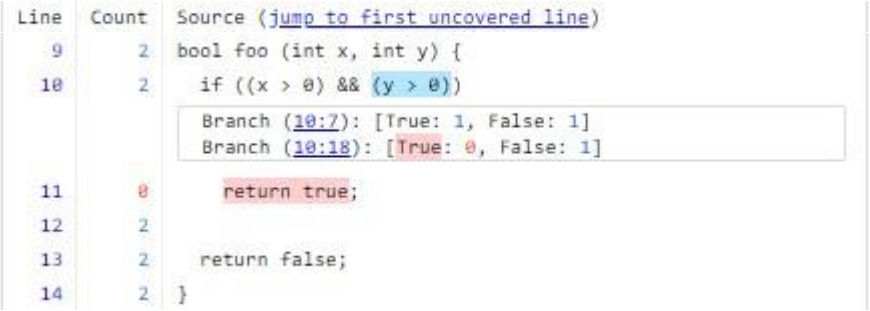
```
Line |   Cnt |
   9|       |bool foo(int x, int y) {
  10|      4|  if ((x > 0) && (y > 0))
                              ^1
  11|      1|    return true;
  12|       |
  13|      3|  return false;
  14|      3|}
```

```
Line |   Cnt |
   9|       |bool foo(int x, int y)
  10|      4|{
  11|      4|  return ((x > 0) && (y > 0));
                                   ^1
  12|      4|}
```

- There are two *conditions* on line 10 that form a *decision*: **`(x > 0), (y > 0)`**
- Line 11 shows that “return true” was executed once
  - What was the execution path through the control flow that *facilitated* this?
  - What was the execution path through the control flow *around* this?
  - **If we don’t know, *we can’t be sure we are executing all paths!***
- Branch Coverage tells us this!
  - How many times is each condition *taken* (True) or *not taken* (False)?

LLVM Coverage Visualization + Branch Coverage

- LLVM Coverage Utility (llvm-cov)



Line	Count	Source (jump to first uncovered line)
9	2	bool foo (int x, int y) {
10	2	if ((x > 0) && (y > 0))
		Branch (10:7): [True: 1, False: 1]
		Branch (10:18): [True: 0, False: 1]
11	0	return true;
12	2	
13	2	return false;
14	2	}

Coverage Report

Created: 2020-09-02 17:42

Click here for information about interpreting this report.

Filename	Function Coverage	Line Coverage	Region Coverage	Branch Coverage
scratch/aphipps/llvmtest/cov/demo/brdemo.cc	100.00% (2/2)	96.15% (25/26)	90.00% (9/10)	83.33% (5/6)
Totals	100.00% (2/2)	96.15% (25/26)	90.00% (9/10)	83.33% (5/6)

Generated by llvm-cov -- llvm version 12.0.0git

- Text (llvm-cov)

```
    9|      2|bool foo (int x, int y) {
   10|      2|  if ((x > 0) && (y > 0))
  ------------------
  |  Branch (10:7): [True: 1, False: 1]
  |  Branch (10:18): [True: 0, False: 1]
  ------------------
   11|      0|    return true;
   12|      2|
   13|      2|  return false;
   14|      2|}
```

Goal: Ensure 100% Branch Coverage

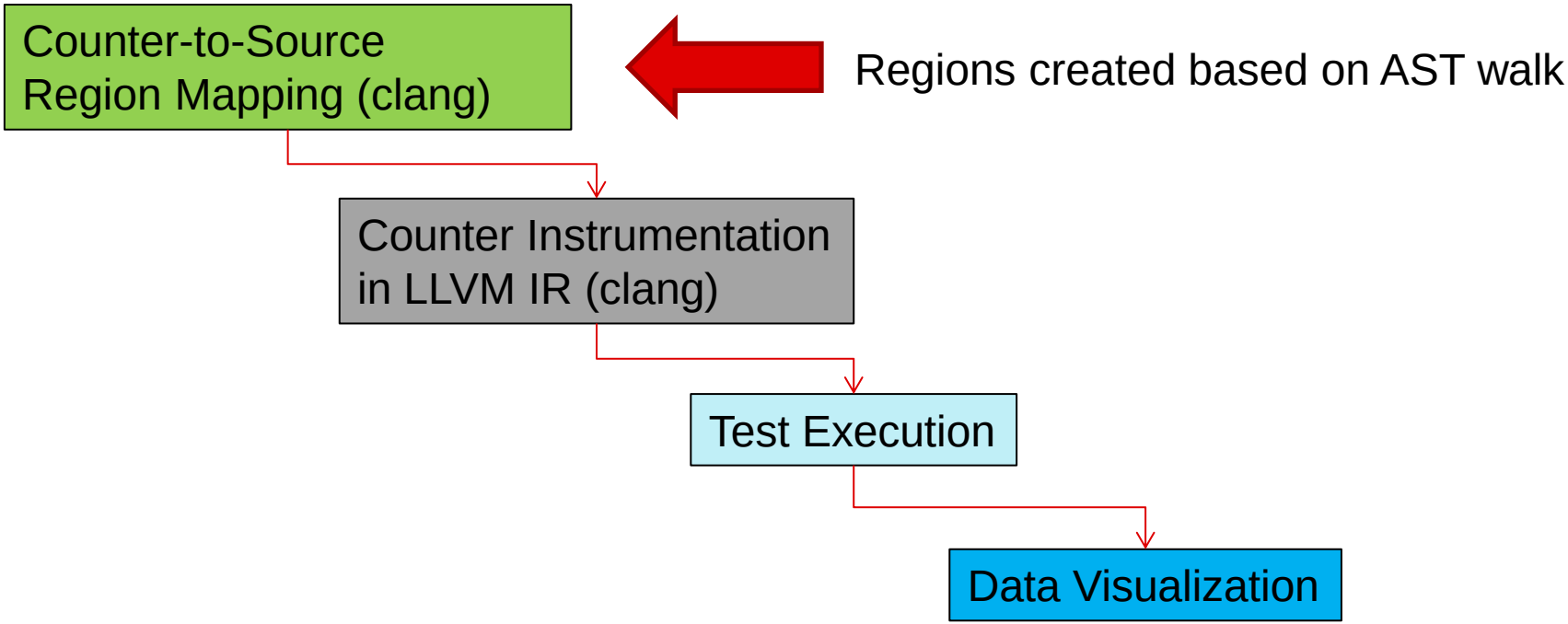
- C *short-circuit semantics* on logical operators
  - Testing all individual conditions *also tests corresponding decisions*

```
bool foo(int x, int y) {
  if ((x > 0) && (y > 0))
    return true;

  return false;
}
```

```
foo(1, 0): (x > 0) = true
           (y > 0) = false
(x > 0) && (y > 0) = false

foo(0, 1): (x > 0) = false
           (y > 0) = … not executed!
(x > 0) && (y > 0) = false

foo(1, 1): (x > 0) = true
           (y > 0) = true
(x > 0) && (y > 0) = true
```

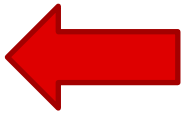
How is Branch Coverage implemented?

Clang Source Region Creation

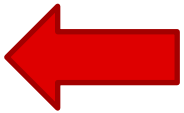


CounterMappingRegion

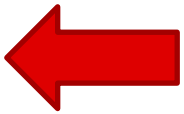
```
struct CounterMappingRegion {
  enum RegionKind {
    /// A CodeRegion associates some code with a counter.
    CodeRegion,

    /// An ExpansionRegion represents a file expansion region that associates
    /// a source range with the expansion of a virtual source file, such as
    /// for a macro instantiation or #include file.
    ExpansionRegion,

    /// A SkippedRegion represents a source range with code that was skipped
    /// by a preprocessor or similar means.
    SkippedRegion,

    /// A GapRegion is like a CodeRegion, but its count is only set as the
    /// line execution count when its the only region in the line.
    GapRegion,

    /// A BranchRegion represents leaf-level boolean expressions and is
    /// associated with two counters, each representing the number of times the
    /// expression evaluates to true or false.
    BranchRegion
  };

  /// Primary Counter that is also used for Branch Regions (TrueCount).
  Counter Count;

  /// Secondary Counter used for Branch Regions (FalseCount).
  Counter FalseCount;

  unsigned FileID, ExpandedFileID;
  unsigned LineStart, ColumnStart, LineEnd, ColumnEnd;
```



CounterMappingRegion associates a source range with a counter. It uses **RegionKind** to identify how to interpret its data.



1.) Extend **RegionKind** to include a new **BranchRegion** kind to represent branch-generating conditions



2.) Use existing **Counter** to represent “True” **BranchRegion** counts

3.) Add a second **Counter** to represent “False” **BranchRegion** counts

Counter Region Mapping (clang)

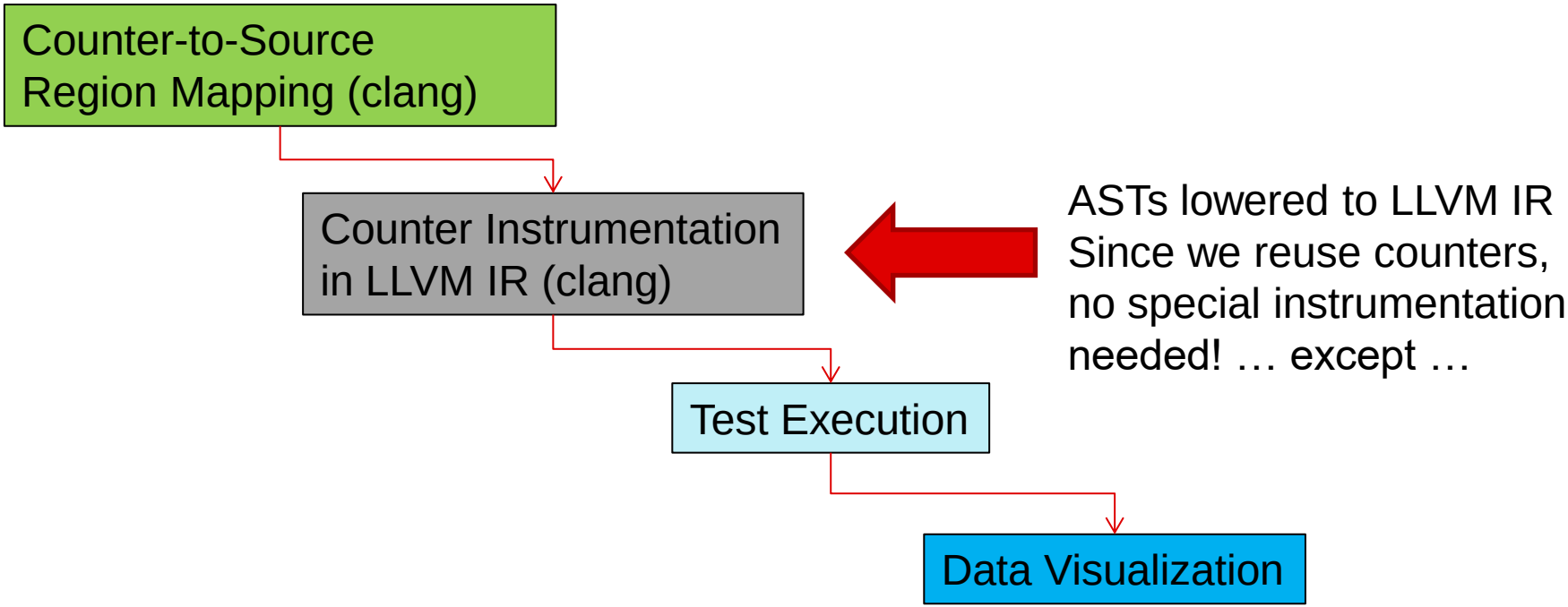
- Instrumentation profile **Counter**s are already created for statement regions
  - We can *trivially* reuse them to calculate Branch condition counts!
  - A **Counter** can also refer to an arithmetic expression between two counters

```
Counter1++
if ( C ) {
    Counter2++
    …

}
```

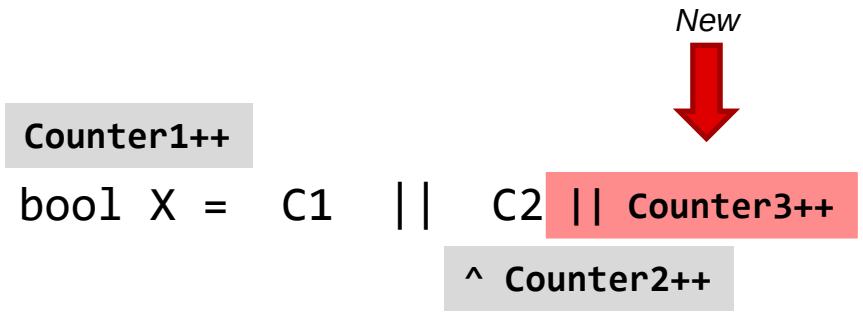
- **Counter1** maps to “Parent” region
- **Counter2** maps to If-Stmt “Then” region
- For **BranchRegion(C)**
  - C.TrueCounter = Counter2
  - C.FalseCounter = Counter1 – Counter2

This is true for all control-flow statements: `if`, `for`, `while`, `switch`, `ternary ?:`

Clang Counter Instrumentation



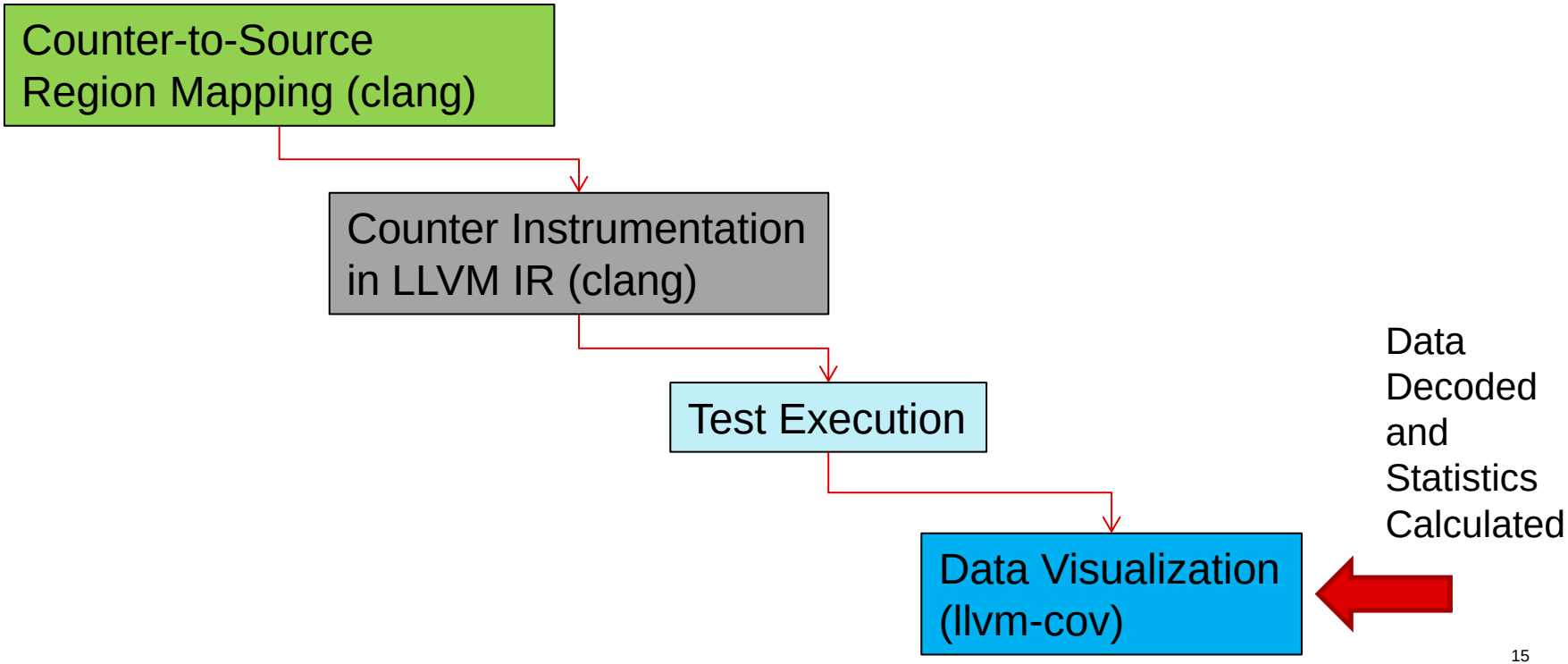
Counter Instrumentation for Logical Operators



- **Counter1** maps to “Parent” region
- **Counter2** maps to “C2”, the right-hand-side, representing C2 *execution count*
- C short-circuit semantics on logical operators
  - *Counter2 increments **only** when C1 is false*
- For **BranchRegion(C1)**
  - C1.FalseCounter = Counter2
  - C1.TrueCounter = Counter1 – Counter2
- For **BranchRegion(C2)**
  - C2.FalseCounter = **Counter3**
  - C2.TrueCounter = **Counter2** – **Counter3**

I have to instrument a *new counter* (**Counter3**) to track C2’s counts

Data Visualization



Visualization (llvm-cov)

- Decode mapping regions and filter based on Function and Macro Expansion

```
line  9: bool foo(int x, int y) {
line 10:  if ((x > 0) && (y > 0))
line 11:    return true;
line 12:
line 13:  return false;
line 14: }
```

```
Function (foo)
-   CodeRegion1 (9:24-10:23)
-   CodeRegion2 (11:0-11:12)
-   CodeRegion3 (12:0-14:0)
BranchRegions:
-   BranchRegion1 (10:5-10:11)
-   BranchRegion2 (10:16-10:22)
```

```
line 18: #define MAX(x,y) ((x) > (y) ? (x) : (y))
```

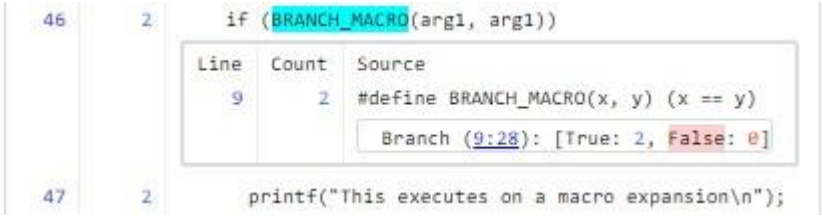
```
Expansion (MAX)
-   CodeRegion1 (18:18-18:40)
BranchRegions:
-   BranchRegion1 (18:19-18:24)
```

```
line 19: bool bar(int x, int y) {
line 20:  return MAX(x,y);
line 24: }
```

```
Function (bar)
-   CodeRegion1 (19:24-24:0)
-   ExpansionRegion1 (20:10-20:13)
```

Visualization (llvm-cov) SubViews

- Extend notion of region **SubView** to include branches
  - **SubViews** are demarcated nested views in the source-code
  - Branches on the same line are grouped into the same **SubView**
  - **SubViews** are also used to demarcate macro expansions
    - Macro expansions can be recursive
    - Macro expansions can contain conditions



- Extend summary reports to include Branch Coverage
  - Add **BranchCoverageInfo** class

`BranchCoverageInfo`
- Total # of Branches (2 per region)
- # Branches executed *at least once*

Branch Coverage Future Optimizations

- Better counter reuse for logical operators
  - Nested conditions: `bool myval = (C1 && C2 && (C3 || C4));`

- Enable HTML ToolTip “hover” capability on source conditions
  - Hovering will reveal actual True/False Branch Counts
  - Similar to how region coverage counts show up today

- Better identification of special branch regions
  - Identify an *implicit* `default` Case in a `switch` statement
  - Identify the sense of constant-folded conditions: *always* True or *never* True

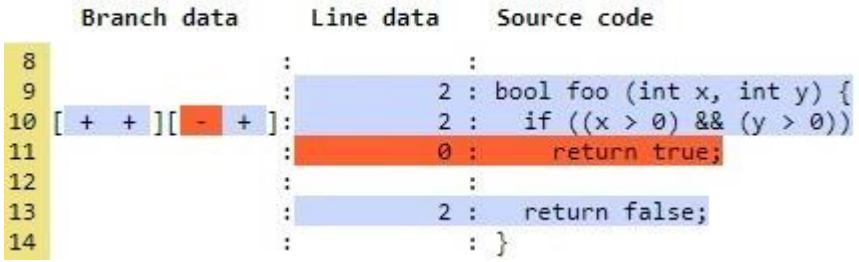
What's Next: MC/DC

- **Ultimate Goal**: Modified Condition/Decision Coverage (MC/DC)
  - Percentage of all condition outcomes that *independently* affect a decision outcome
  - *Built on top of branch-coverage*

- Usually involves emitting a truth table to confirm all possibilities

Observations on GCC Branch Coverage

- GCC HTML (LCOV)



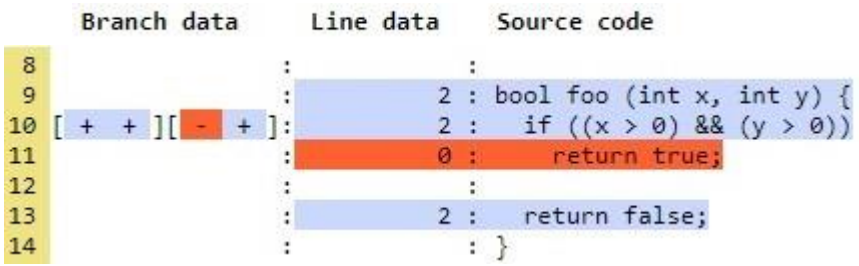
- GCC Text (GCOV)

```
function _Z3fooii called 2 returned 100% blocks executed 80%
        2:    9:bool foo (int x, int y) {
        2:   10:  if ((x > 0) && (y > 0))
branch  0 taken 1 (fallthrough)
branch  1 taken 1
branch  2 taken 0 (fallthrough)
branch  3 taken 1
    #####:   11:    return true;
        -:   12:
        2:   13:  return false;
        -:   14:}
```

- True/False Branch Data shown
  - "+" → Executed at least once
  - "-" → Not Executed (i.e. "0")
  - Hover to see counts
- Difficult to tie branches to source
  - Which branch goes with which condition?
  - Which branch represents taken vs not taken?
- In other contexts…
  - May see additional branches that **aren't visible** in source code
  - Some branches may be removed
    - GCC advises against using optimization with code coverage

GCC vs. LLVM

- GCC HTML (LCOV)



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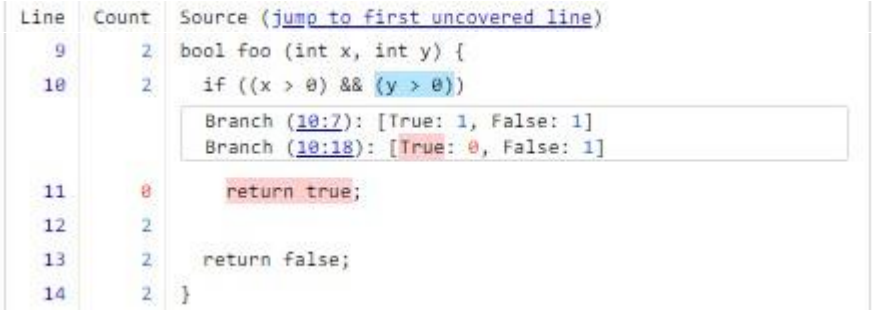
- LLVM HTML



- LLVM Text

```
    9|      2|bool foo (int x, int y) {
   10|      2|  if ((x > 0) && (y > 0))
  ------------------
  |  Branch (10:7): [True: 1, False: 1]
  |  Branch (10:18): [True: 0, False: 1]
  ------------------
   11|      0|    return true;
   12|      2|
   13|      2|  return false;
   14|      2|}
```

Current State of LLVM Branch Coverage

- Implementation is complete -- in the process of upstreaming the work!
  - Phabricator Review https://reviews.llvm.org/D84467
- Should be included with stock LLVM Source-based Code Coverage
- A lot of ways to improve branch coverage! Want to be involved?
  - Contact me! a-phipps@ti.com

Thank you!

- Acknowledgements
  - Vedant Kumar, Apple
  - Cody Addison, Nvidia
  - Alan Davis, Texas Instruments