# LLVM & LLVM Bitcode Introduction

# What is LLVM ? (1/2)

- LLVM (Low Level Virtual Machine) is a compiler infrastructure
  - Written by C++ & STL
- History
  - The LLVM project started in 2000 at the University of Illinois
  - BSD-style license (Berkeley Software Distribution License)
  - LLVM: A compilation framework for lifelong program analysis & transformation (a published paper by Chris Lattner, Vikram Adve)(CGO 04)
  - 2005, Apple hired Chris Lattner

Chris Lattner

LLVM COMPILER INFRASTRUCTURE

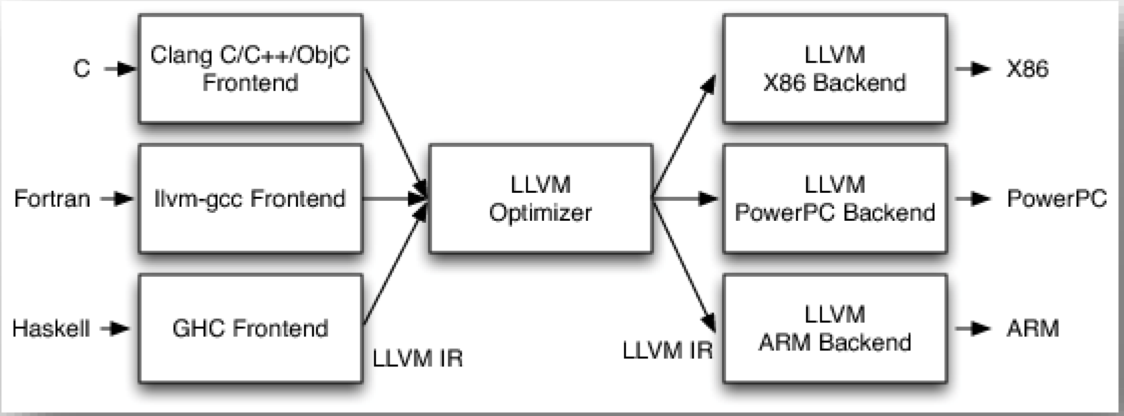
# What is LLVM? (2/2)

- Targets of LLVM
  - Lifelong optimization
  - Integration
    - AOT (ahead-of-time) compiler, JIT (just-in-time) compiler, interpreter
- Compare with GCC
  - More advanced architecture
  - Better optimizations
  - Faster compilation
  - GCC currently support more targets than LLVM

# LLVM retargetablity design

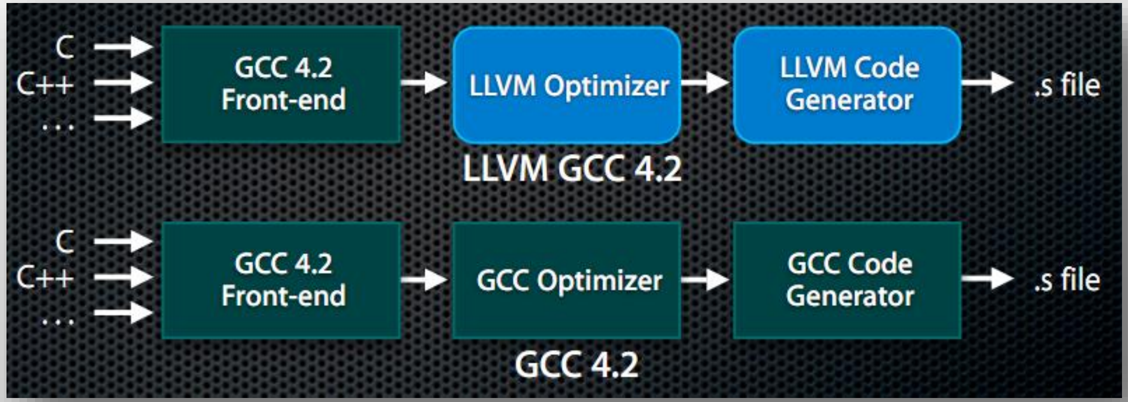
Traditional Three-Phase Compiler design


LLVM retargetablity

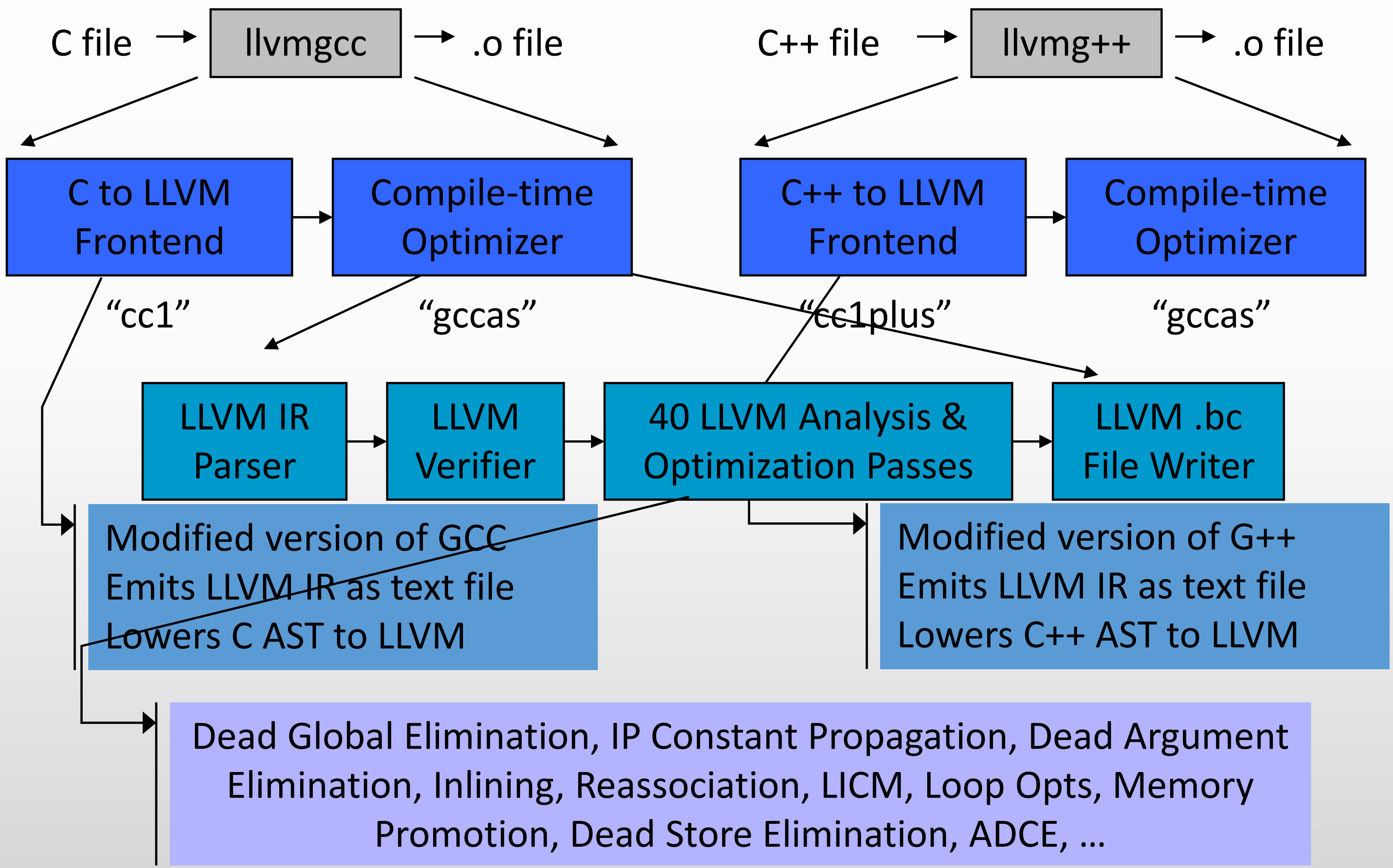


# LLVM tools

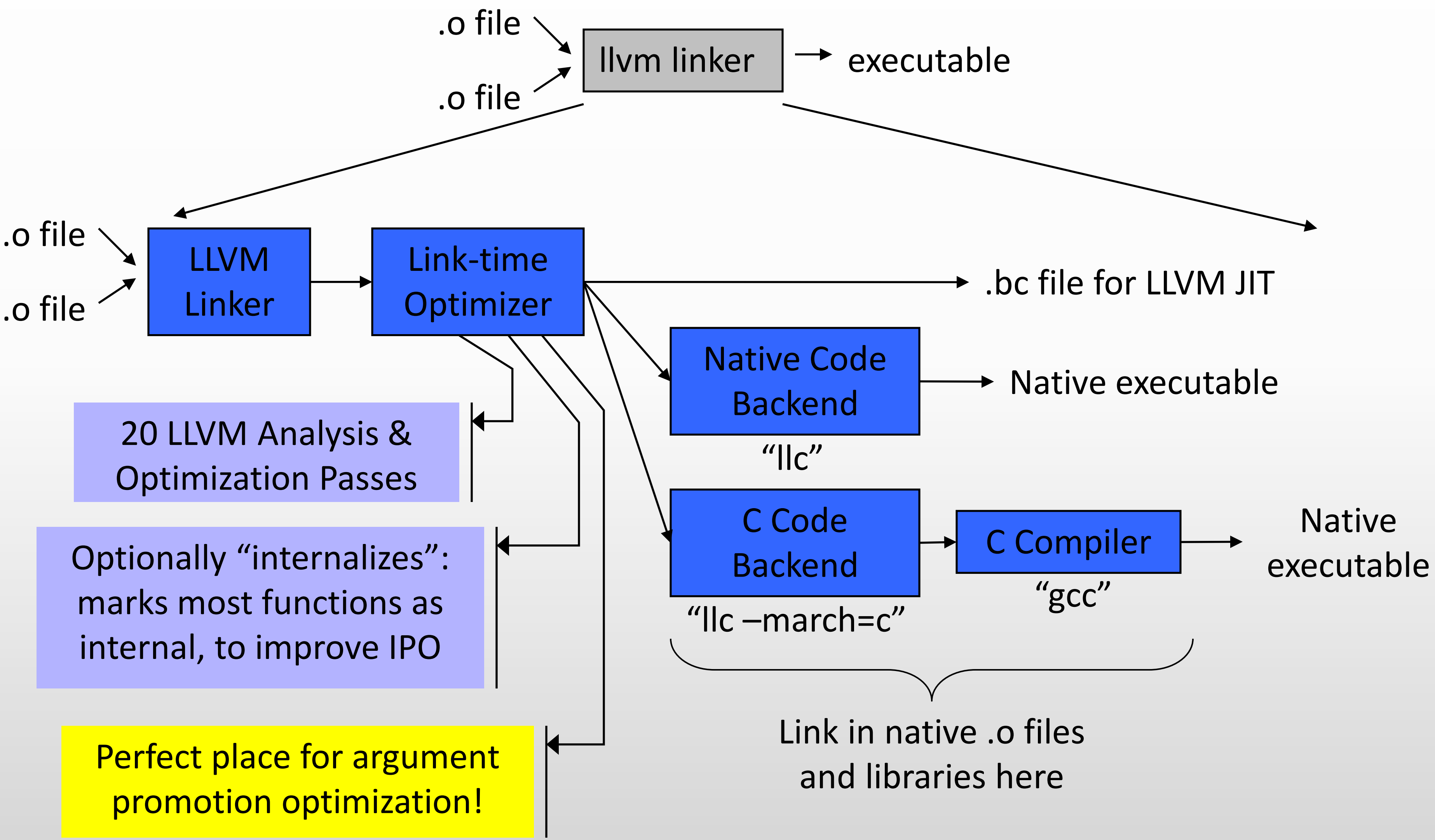
- **llvm-as**: assemble a human-readable .ll file into bitcode
- **llvm-dis**: disassemble a bitcode file into a human-readable .ll file
- **opt**: run a series of LLVM-to-LLVM optimizations on a bitcode file
- **llc**: generate native machine code for a bitcode file
- **lli**: directly run a program compiled to bitcode using a JIT compiler or interpreter
- **llvm-link**: link several bitcode files into one
- **clang**: C, C++, Object C front-end for LLVM
- **llvm-gcc**: GCC-based C front-end for LLVM
- **llvm-g++**: GCC-based C++ front-end for LLVM



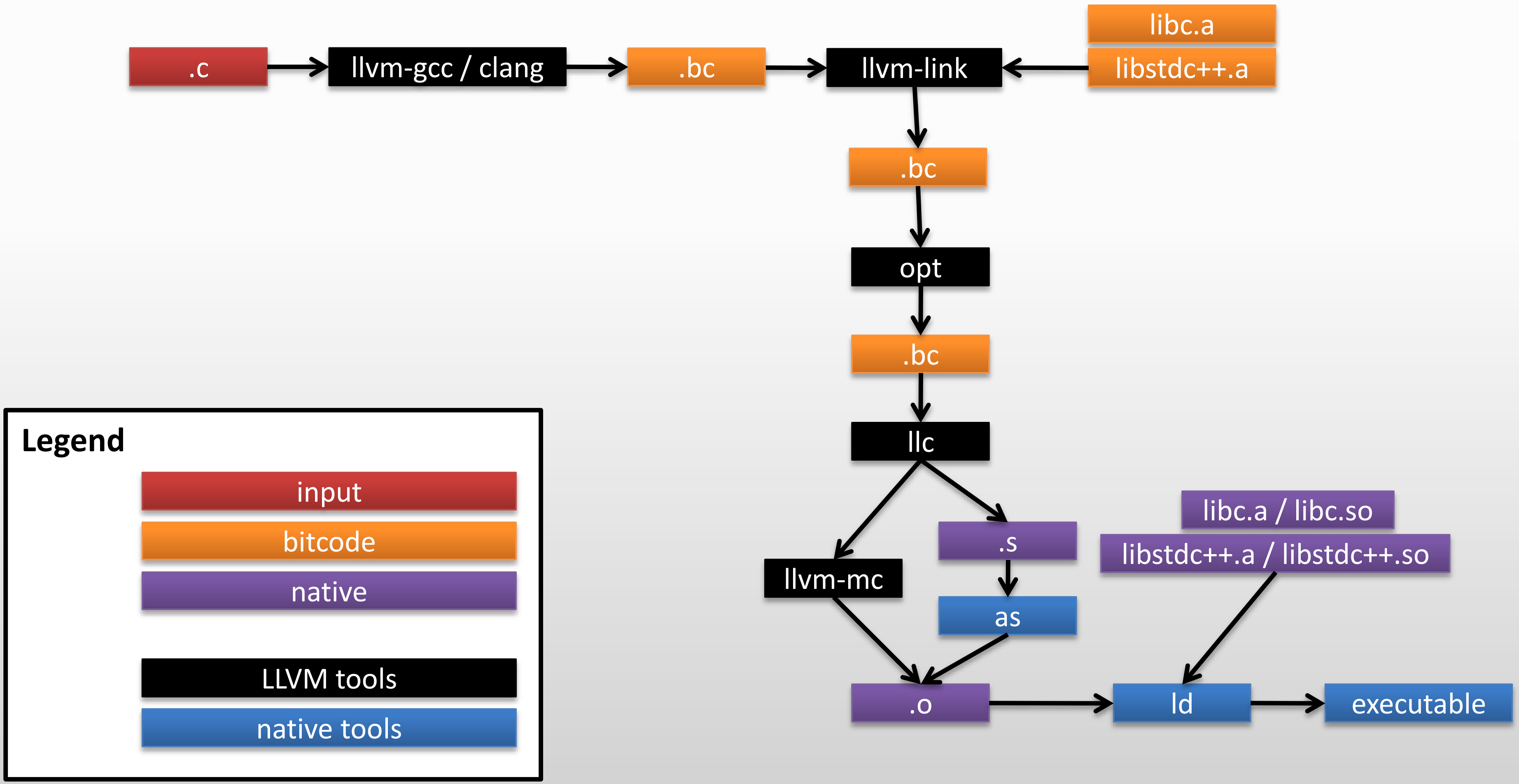
# Looking into events at compile-time



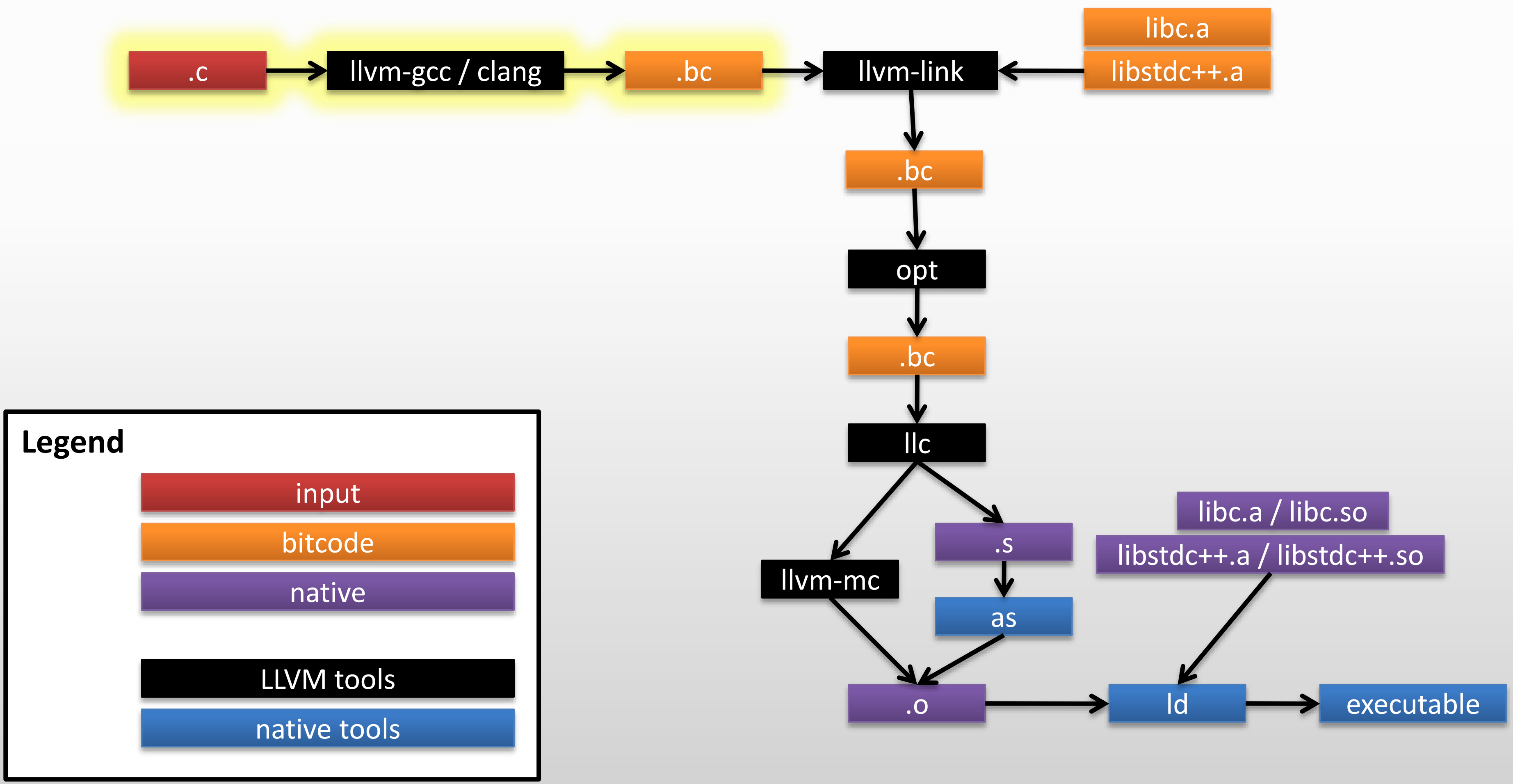
# Looking into events at link-time



# LLVM framework



# Source code to LLVM IR



# LLVM IR

- LLVM code representation
  - In memory compiler IR (Intermediate Representation)
  - Human readable assembly language – LLVM IR (*.ll)
  - On-disk bitcode representation (*.bc)
- LLVM IR is SSA form (Static single assignment form)
  - Each variable is assigned exactly once
  - Use-def chains are explicit and each contains a single element

# Global variable & Array representation

```
long long x[3][3] = {{ 1, 2, 3 }, { 4, 5, 6 }, { 7, 8, 9 }};
long long y[3][3] = {{ 9, 8, 7 }, { 6, 5, 4 }, { 3, 2, 1 }};
long long z[3][3];

int main()
{
        int sum = 0;

        for(int i = 0; i < 3; ++i) {
                for(int j = 0; j < 3; ++j) {
                        z[i][j] = 0;

                        for(int k = 0; k < 3; ++k) {
                                z[i][j] += x[i][k] * y[k][j];
                        }
                }
        }
```

```
@x = global [3 x [3 x i64]]
            [[3 x i64] [i64 1, i64 2, i64 3],
             [3 x i64] [i64 4, i64 5, i64 6],
             [3 x i64] [i64 7, i64 8, i64 9]
            ], align 8
@y = global [3 x [3 x i64]]
            [[3 x i64] [i64 9, i64 8, i64 7],
             [3 x i64] [i64 6, i64 5, i64 4],
             [3 x i64] [i64 3, i64 2, i64 1]
            ], align 8
@z = common global [3 x [3 x i64]] zeroinitializer, align 8
```

# Function entry & Local variables

```
long long x[3][3] = {{ 1, 2, 3 }, { 4, 5, 6 }, { 7, 8, 9 }};
long long y[3][3] = {{ 9, 8, 7 }, { 6, 5, 4 }, { 3, 2, 1 }};
long long z[3][3];

int main()
{
        int sum = 0;

        for(int i = 0; i < 3; ++i) {
                for(int j = 0; j < 3; ++j) {
                        z[i][j] = 0;

                        for(int k = 0; k < 3; ++k) {
                                z[i][j] += x[i][k] * y[k][j];
                        }
                }
        }
```

```
define i32 @main() nounwind {
entry:
  %retval = alloca i32                          ; <i32*> [#uses=2]
  %k = alloca i32                               ; <i32*> [#uses=6]
  %j = alloca i32                               ; <i32*> [#uses=8]
  %i = alloca i32                               ; <i32*> [#uses=8]
  %sum = alloca i32                             ; <i32*> [#uses=4]
  %"alloca point" = bitcast i32 0 to i32        ; <i32> [#uses=0]
```

# Inner-most loop

```
long long x[3][3] = {{ 1, 2, 3 }, { 4, 5, 6 }, { 7, 8, 9 }};
long long y[3][3] = {{ 9, 8, 7 }, { 6, 5, 4 }, { 3, 2, 1 }};
long long z[3][3];

int main()
{
        int sum = 0;

        for(int i = 0; i < 3; ++i) {
                for(int j = 0; j < 3; ++j) {
                        z[i][j] = 0;

                        for(int k = 0; k < 3; ++k) {
                                z[i][j] += x[i][k] * y[k][j];
                        }
                }
        }
```

```
bb2:                                                ; preds = %bb3
  %5 = load i32* %i, align 4                        ; <i32> [#uses=1]
  %6 = load i32* %j, align 4                        ; <i32> [#uses=1]
  %7 = load i32* %i, align 4                        ; <i32> [#uses=1]
  %8 = load i32* %j, align 4                        ; <i32> [#uses=1]
  %9 = getelementptr inbounds [3 x [3 x i64]]* @z, i32 0, i32 %7 ; <[3 x i64]*> [#uses=1]
  %10 = getelementptr inbounds [3 x i64]* %9, i32 0, i32 %8 ; <i64*> [#uses=1]
  %11 = load i64* %10, align 8                      ; <i64> [#uses=1]
  %12 = load i32* %i, align 4                       ; <i32> [#uses=1]
  %13 = load i32* %k, align 4                       ; <i32> [#uses=1]
  %14 = getelementptr inbounds [3 x [3 x i64]]* @x, i32 0, i32 %12 ; <[3 x i64]*> [#uses=1]
  %15 = getelementptr inbounds [3 x i64]* %14, i32 0, i32 %13 ; <i64*> [#uses=1]
  %16 = load i64* %15, align 8                      ; <i64> [#uses=1]
  %17 = load i32* %k, align 4                       ; <i32> [#uses=1]
  %18 = load i32* %j, align 4                       ; <i32> [#uses=1]
  %19 = getelementptr inbounds [3 x [3 x i64]]* @y, i32 0, i32 %17 ; <[3 x i64]*> [#uses=1]
  %20 = getelementptr inbounds [3 x i64]* %19, i32 0, i32 %18 ; <i64*> [#uses=1]
  %21 = load i64* %20, align 8                      ; <i64> [#uses=1]
  %22 = mul i64 %16, %21                            ; <i64> [#uses=1]
  %23 = add nsw i64 %11, %22                        ; <i64> [#uses=1]
  %24 = getelementptr inbounds [3 x [3 x i64]]* @z, i32 0, i32 %5 ; <[3 x i64]*> [#uses=1]
  %25 = getelementptr inbounds [3 x i64]* %24, i32 0, i32 %6 ; <i64*> [#uses=1]
  store i64 %23, i64* %25, align 8
  %26 = load i32* %k, align 4                       ; <i32> [#uses=1]
  %27 = add nsw i32 %26, 1                          ; <i32> [#uses=1]
  store i32 %27, i32* %k, align 4
  br label %bb3
```

# LLVM command

- Generate the *.bc
  - $ clang  -c –emit-llvm a.c  –o a.bc
  - $ llvm-dis a.bc  -o a.ll
- Generate the *.ll (human-readable)
  - $ clang –S –emit-llvm a.c –o a.ll
- Using interpreter to run bitcode
  - $ lli test.bc

# How to build the LLVM

- http://llvm.org/docs/GettingStarted.html#getting-started
- Download llvm 3.2, clang., Compiler-RT from http://llvm.org/releases/download.html#3.2

```
$ tar zxf llvm-3.2.src.tar.gz
$ cd llvm-3.2.src/tool
$ tar zxf clang-3.2.src.tar.gz
$ mv clang-3.2.src.tar.gz clang
$ cd llvm-3.2.src/projects
$ tar zxf compiler-rt-3.2.src.tar.gz
$ mv compiler-rt-3.2.src compiler-rt
$ cd where-you-want-to-build-llvm
$ ../llvm/configure
$ make
```

# LLVM conclusion

- Integration
  - Ex: clang for static compiler and for JIT compiler
- Low level IR
  - SSA-based
  - Language-independent
  - Machine-independent
  - Allow libraries and portions written by different language
- More and more languages and targets support

# Reference

- LLVM official website
  - http://llvm.org/
  - http://llvm.org/docs/GettingStarted.html
- LLVM IR
  - http://llvm.org/docs/LangRef.html