Contemporary Compilers

by Aaron Myles Landwehr

LLVM

- Formally “**L**ow **L**evel **V**irtual **M**achine”
- A Compiler written in C++ (no exceptions or RTTI) – see here.
  - Started in 2000 at University of Illinois at Urbana–Champaign.
  - BSD-Style License (not a Copyleft license: no restrictions on how code is used)
  - Started by Chris Lattner (now at Apple)
  - Compiles IR into target ASM (or Machine Code)
    - No linking though – **yet**: must use a separate linker (gnu ld, msvc link.exe, gold, OSX Linker, MCLinker).
- Primary compiler for OSX user-land and IOS (OSX Kernel is still GCC)
  - Apple took interest for a number of reasons:
    - LLVM has a less restictive license than GCC.
    - Objective-C: low priority for gcc - stagnant.
    - GCC more difficult to hack.

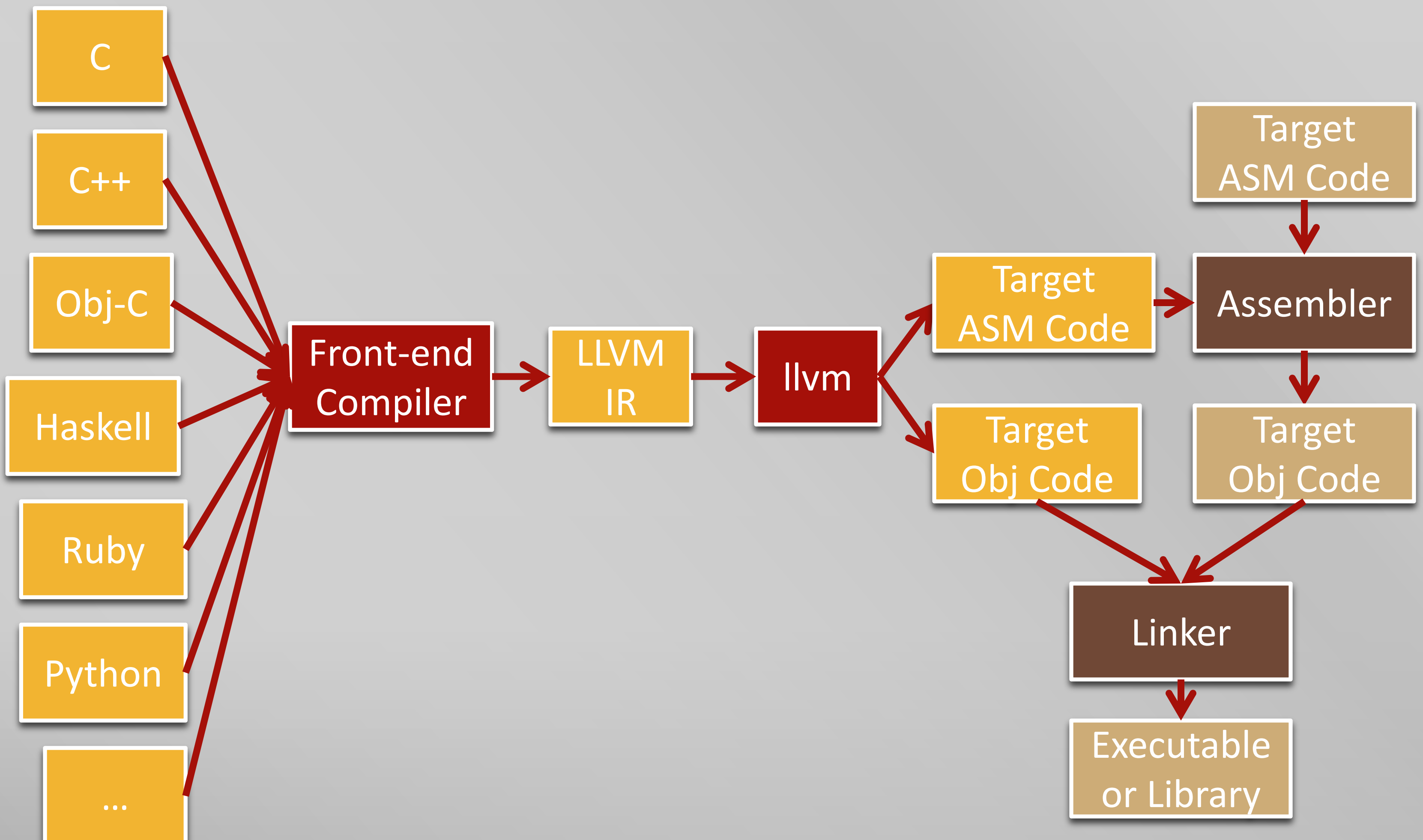
Clang

- Compiler Front end for LLVM.
- Compiles C, C++, Objective-C, and Objective-C++ into LLVM IR.
- Using Clang in conjunction with LLVM replaces the GCC stack.

Why use LLVM?

- Modern Compiler (with an arguably modular design).
- Language Agnostic.
- Better documentation (compared to alternatives).
- Less restrictive license.
- Easier to extend, add optimizations, add new targets, etc.

LLVM Toolchain at a High-Level



LLVM ASM (Intermediate Representation)

- A Static Single Assignment (SSA) based representation that provides type safety, low-level operations, flexibility, and the capability of representing 'all' high-level languages cleanly.
- Contains many instructions normally found in target assemblies:
  - Binary operations:
    - ret, br, add, sub, mul, udiv, sdiv, urem, srem, fadd, fsub, fmul, fdiv.
  - Bitwise operations:
    - shl, lshr(logical), ashr (arithmetic), and, or, xor
  - Comparisons
    - icmp, fcmp (perhaps, ASMs don’t normally have this form).
  - Memory operations
    - load, store, cmpxchg

Other Instructions in the LLVM IR

- Contains many other operations:
  - phi, select, call, va_arg, fence, getelementptr, switch, *et cetera*.
- Conversion operations:
  - trunct, zext, sext, fptrunc, fpext, fptoui, fptosi, uitofp, sitofp, ptrtoint, inttoptr, bitcast
- Intrinsic functions
  - memcpy, cos, sin, log, exp, pow, *et cetera.*

IR Type System

- The IR is strongly typed .
- Instructions use these types:
  - Integer

    i1, i2, i3, ... i8, ... i16, ... i32, ... i64, ...
  - Float
    - Half, float, double,
    - fp128 (128-bit floating point value (112-bit mantissa)),
    - x86_fp80 (80-bit floating point value (X87)),
    - ppc_fp128 (128-bit floating point value (two 64-bits))
  - Pointer, vector, structure, array, label, meta data.
  - Others…

LLVM IR Closer to High Level

- The IR supports global variables, functions, aliases, linkage types.
- Has more in common with a high level language than a normal assembly language. Organized into modules that can be linked together:

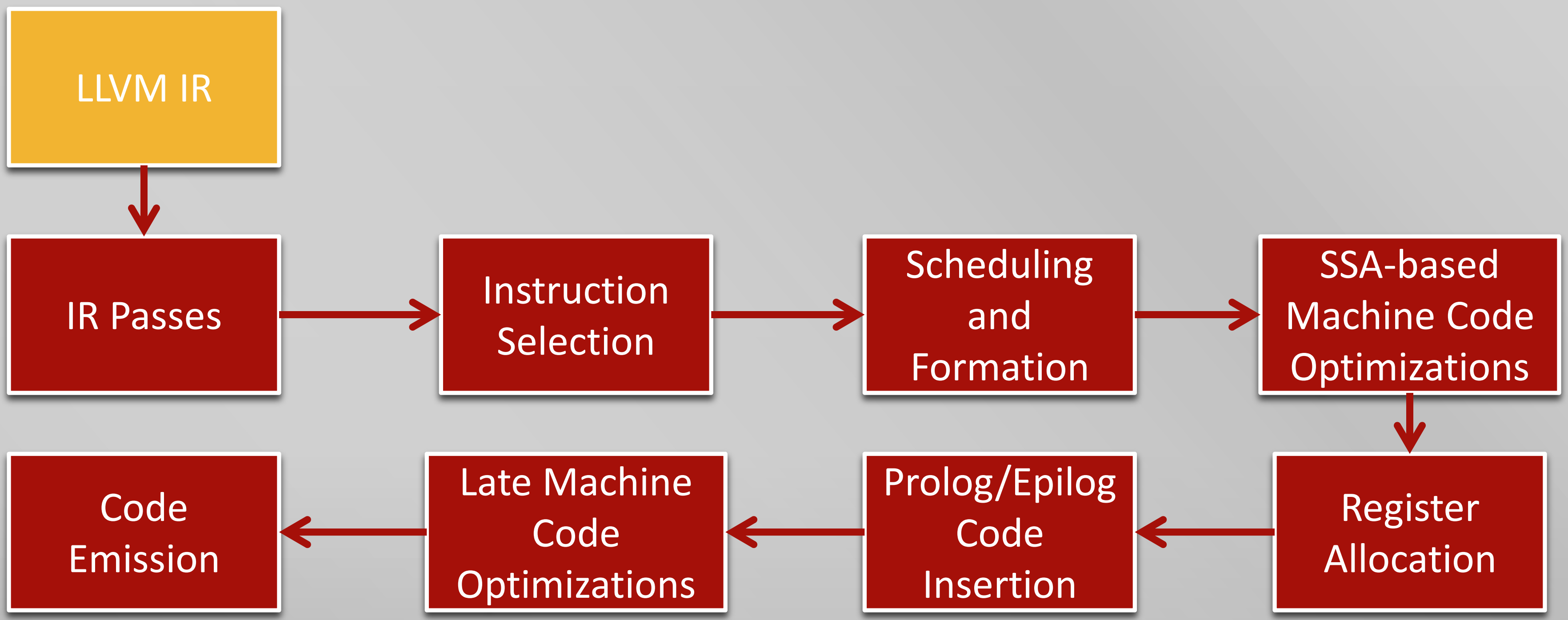
```
; Declare the string constant as a global constant.
@.str = private unnamed_addr constant [13 x i8] c"hello world\0A\00"

; External declaration of the puts function
declare i32 @puts(i8* nocapture) nounwind

; Definition of main function
define i32 @main() {   ; i32()*
  ; Convert [13 x i8]* to i8  *...
  %cast210 = getelementptr [13 x i8]* @.str, i64 0, i64 0

  ; Call puts function to write out the string to stdout.
  call i32 @puts(i8* %cast210)
  ret i32 0
}
```

LLVM IR Example Module (Using ExampleOne)

- How to compile into LLVM IR:
  - clang -O3 -emit-llvm -S exampleOne.c -o exampleOne.ll
- OR
  - View the exampleOne.c and exampleOne.ll files in the additional materials.

LLVM Infrastructure at a Low Level View

- Different Sections to be explained…



For Optimizations, Analysis, and Transformations

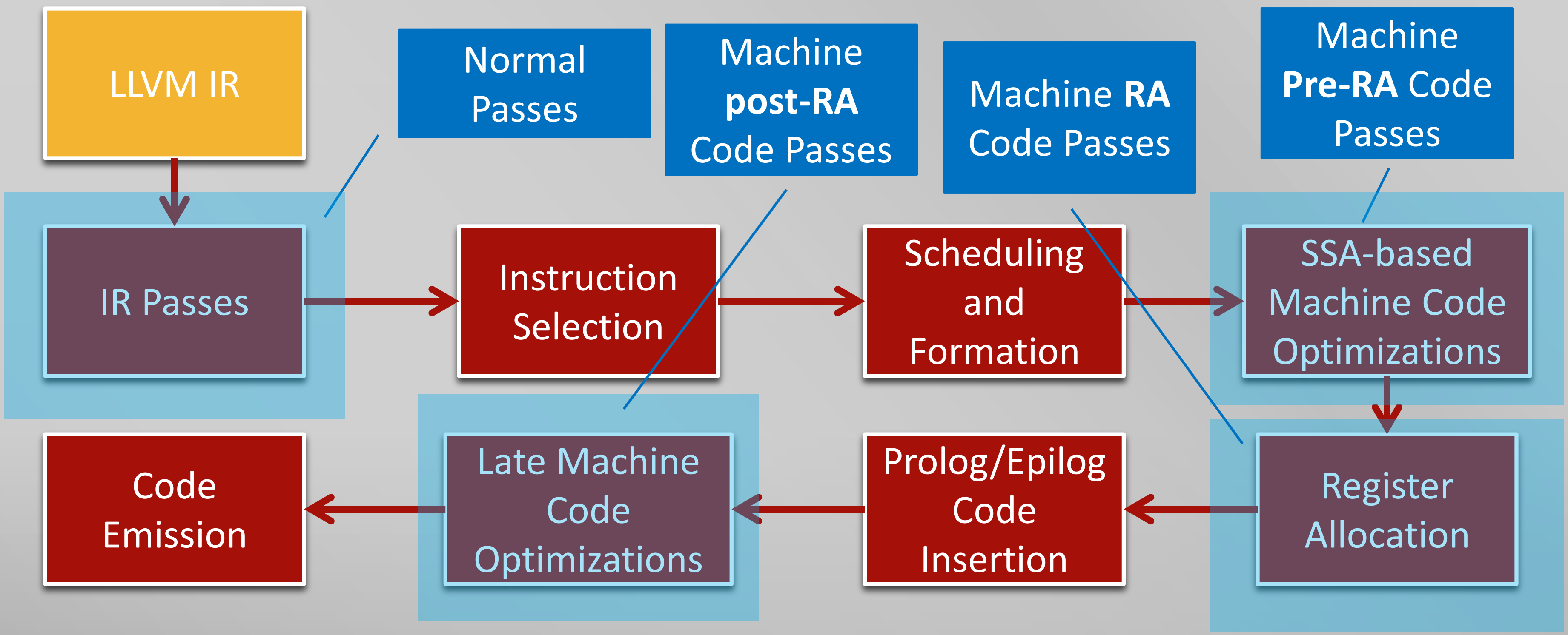
LLVM Passes

LLVM Analysis and Transform Passes

- Passes perform transformations and optimizations that make up the compiler.
- Perform analysis (to aid other transformations, or to aid the programmer).
- They can operate in two distinct phases:
  - Before instruction selection (Operating on the LLVM IR).
    - For applying machine independent optimizations and transformations.
  - After Instruction Selection and Scheduling and Formation
    - Operating on the Machine dependent Representation.
      - Three types: SSA-based/Pre-RA, RA, non-SSA/Post-RA.
    - For applying machine specific optimizations and transformations.
- Support for different types of passes: function, basic block, loop, regions, call graph, etc.
- Mechanisms to handle pipelining passes, dependencies and interactions.

Pass Phases

- One that operates on the high level IR.
- One that operates on the machine representation (Machine Passes).



Example Pass (using exampleTwo and exampleThree)

1. clang -emit-llvm exampleTwo.c -S -o exampleTwo.ll
2. Demo CFG
   - **As a Loadable Module** (AKA Not in Windows ;-)) – See here.
     - opt -load /path/to/llvm/lib/LLVMAViewCFG.so - a-view-cfg exampleTwo.ll > /dev/null
   - **Integrated into Opt:**
     - opt -a-view-cfg exampleTwo.ll > /dev/null
3. Demo Dom
   - opt -view-dom exampleTwo.ll > /dev/null
4. Demo phi nodes
   1. clang -O1 -emit-llvm exampleThree.c -S -o exampleThree.ll
   - opt -a-print-phi exampleThree.ll > /dev/null

Example Pass (using exampleTwo and exampleThree) Cont.

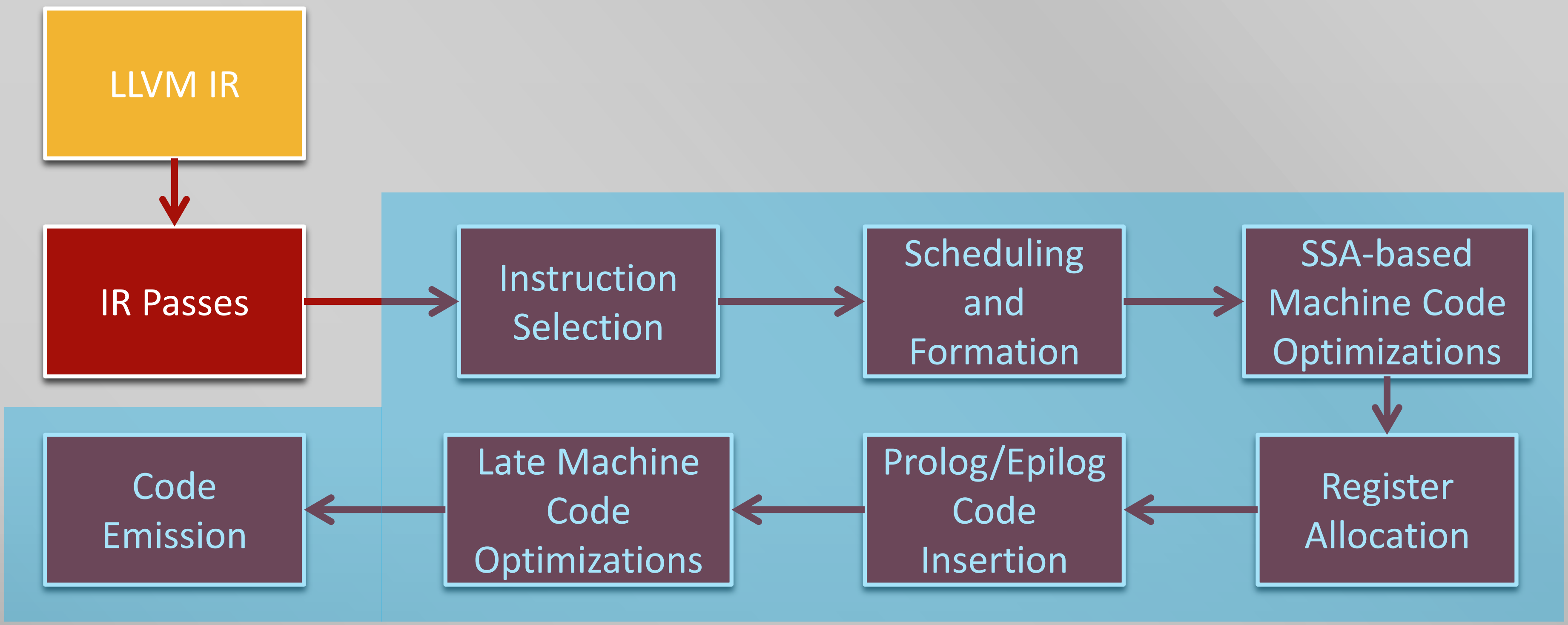
- View the additional materials:
  - exampleTwo_CFG.dot – Control Flow Graph.
  - exampleTwo_DOM.dot – Dominator Tree.
  - exampleThree_PHI.txt – Phi Nodes.
  - Additionally, look at the corresponding .ll files for the llvm IR.

The Bulk of LLVM

LLVM Target Independent Code Generator

LLVM Target Independent Code Generator

- A framework that provides a suite of reusable components for translating the LLVM internal representation to the machine code for a specified target.



Instruction Selection

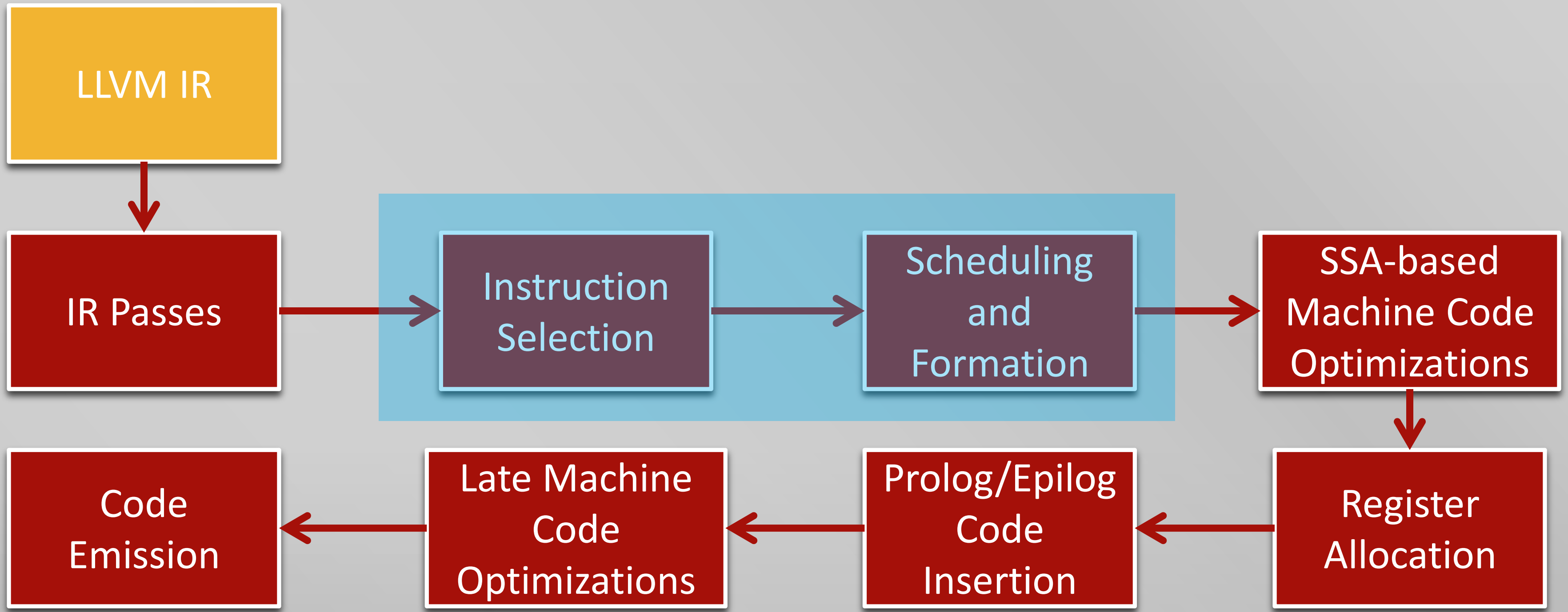
- Instruction Selection is the process of translating LLVM code presented to the code generator into target-specific machine instructions.
- LLVM uses a SelectionDAG based instruction selector.
  - The nodes are of type SDNode (e.g. specialized classes inheriting from it).
    - e.g. LoadSDNode, StoreSDNode, …
  - Instruction Selection is done programmatically and with pattern matching.

Example SelectionDAG (Uses exampleOne)

- View the additional materials:
  - exampleOne_DAG.dot
- Programmatically:
  - cgdb --args llc exampleOne.ll
  - b DAGCombiner.cpp:Run
  - run
  - call DAG.viewGraph()

Phases that Use the SelectionDAG

- Only two phases operate on the Selection DAG.



Instruction Selection Cont.

- Build initial DAG
  - Simple translation into a DAG from the input IR (Contains illegal Ops).
- Optimize SelectionDAG
  - Simplify the DAG. Programmatically done (and ad-hoc)
  - See **CodeGen/SelectionDAG/DAGCombiner.cpp**
- Legalize SelectionDAG Types
  - Eliminate any types that are not supported by the target.
  - E.g. if the target doesn’t support 32 bit types, it may promote them to 64 bit types.
  - See **lib/Target/TARGETNAME/TARGETNAMEISelLowering.cpp**

Instruction Selection Cont. 2

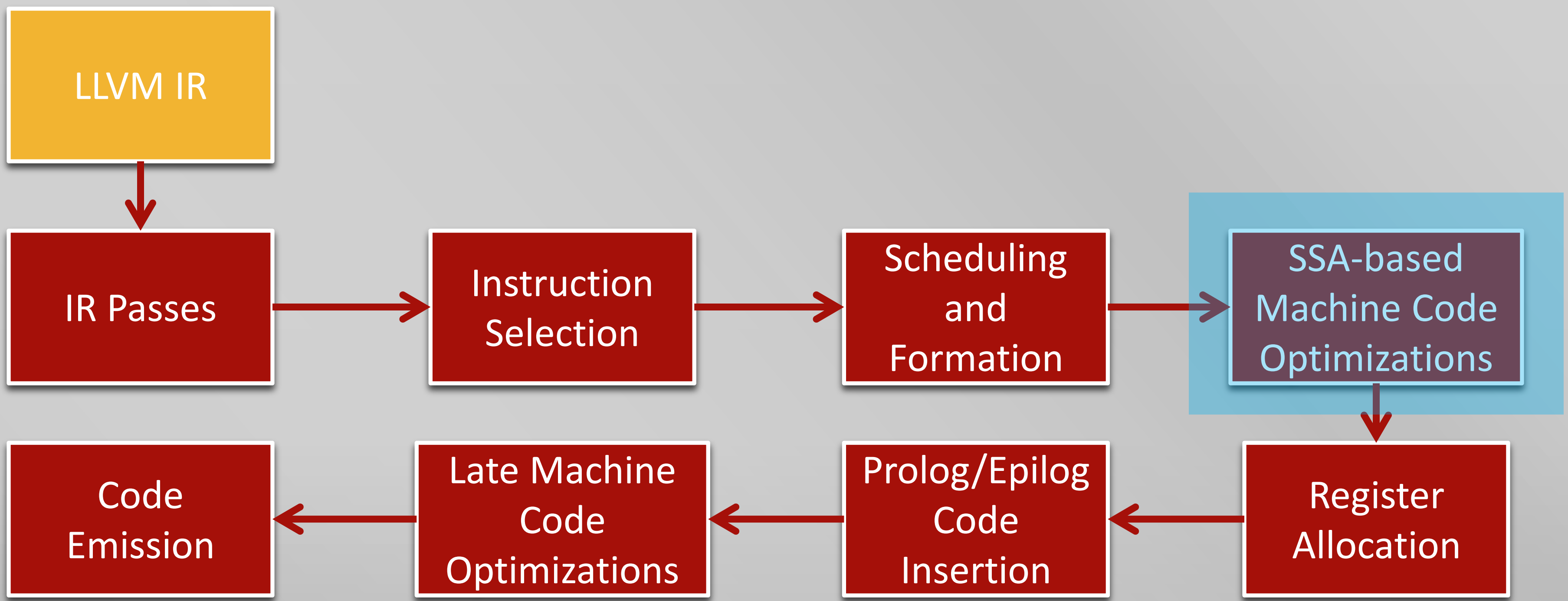
- Optimize SelectionDAG
- Legalize SelectionDAG Ops
  - Eliminate operations not natively supported by the target.
  - See **lib/Target/TARGETNAME/TARGETNAMEISelLowering.cpp**
- Optimize SelectionDAG
- Select instructions from the DAG
  - Takes a legal Target-independent SelectionDAG as input and outputs a Target SelectionDAG.
  - Done via Pattern Matching (mostly).
  - In some cases it is easier to eliminate non-native operations during this phase.
  - See **lib/Target/TARGETNAME/*.td** files.

Scheduling and Formation

- This phase takes a Target SelectionDAG and assigns an order to the operations.
  - The scheduler can pick an order depending on various constraints of the machines.
- Once the order is established, the SelectionDAG is converted into a list of Machine Instructions.

LLVM Infrastructure at a Low Level View

- Where we are next…



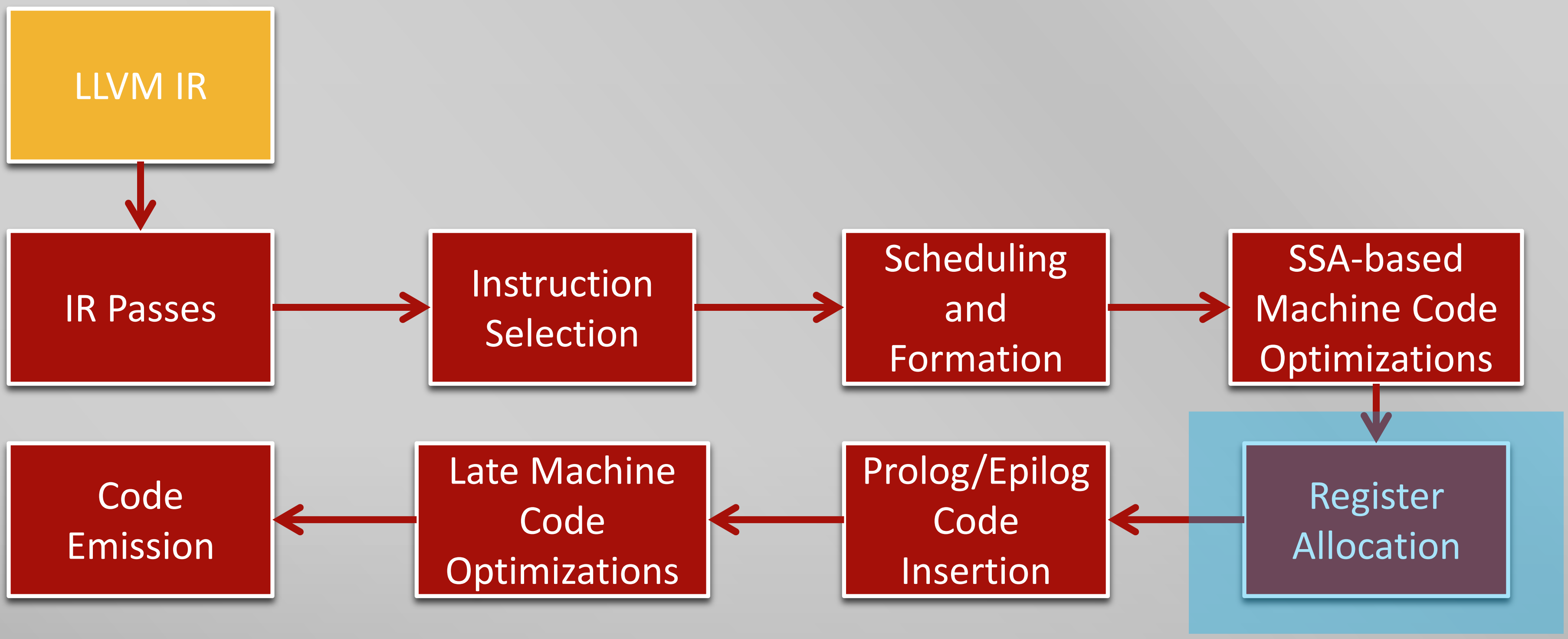
SSA-based Machine Code Optimizations

- Modulo-scheduling***** and peephole optimizations.
- Implemented as machine passes.
- See **lib/CodeGen/PeepholeOptimizer.cpp**
- This stage is where targets can and have implemented their own **SSA-based/pre-register allocation** machine passes.

- * Doesn't exist anymore – The original implementation was SPARC specific and eventually was clobbered.

LLVM Infrastructure at a Low Level View

- Where we are next…



Register Allocation

- Transform the code from using an infinite virtual register file in SSA form to a concrete register file used by the target.
- Introduces register spilling (including spill code).
- Removed unnecessary copy instructions and replaces Phi instructions.
- Implemented as machine passes.
- Register Allocators
  - Fast – for debug builds, keeps values in registers and reuses registers as appropriate.
  - Basic – Uses live ranges per register one at a time.
  - Greedy – Highly tuned version of Basic that incorporates global live range spilling. (default)
  - PBQP (Partitioned Boolean Quadratic Programming) – Uses a PBQP solver?
  - Linear Scan – Old default register allocator (pre LLVM 3.0).
  - See **Lib/CodeGen/PhiElimination.cpp** & **lib/CodeGen/RegAlloc*.cpp**

LLVM Infrastructure at a Low Level View

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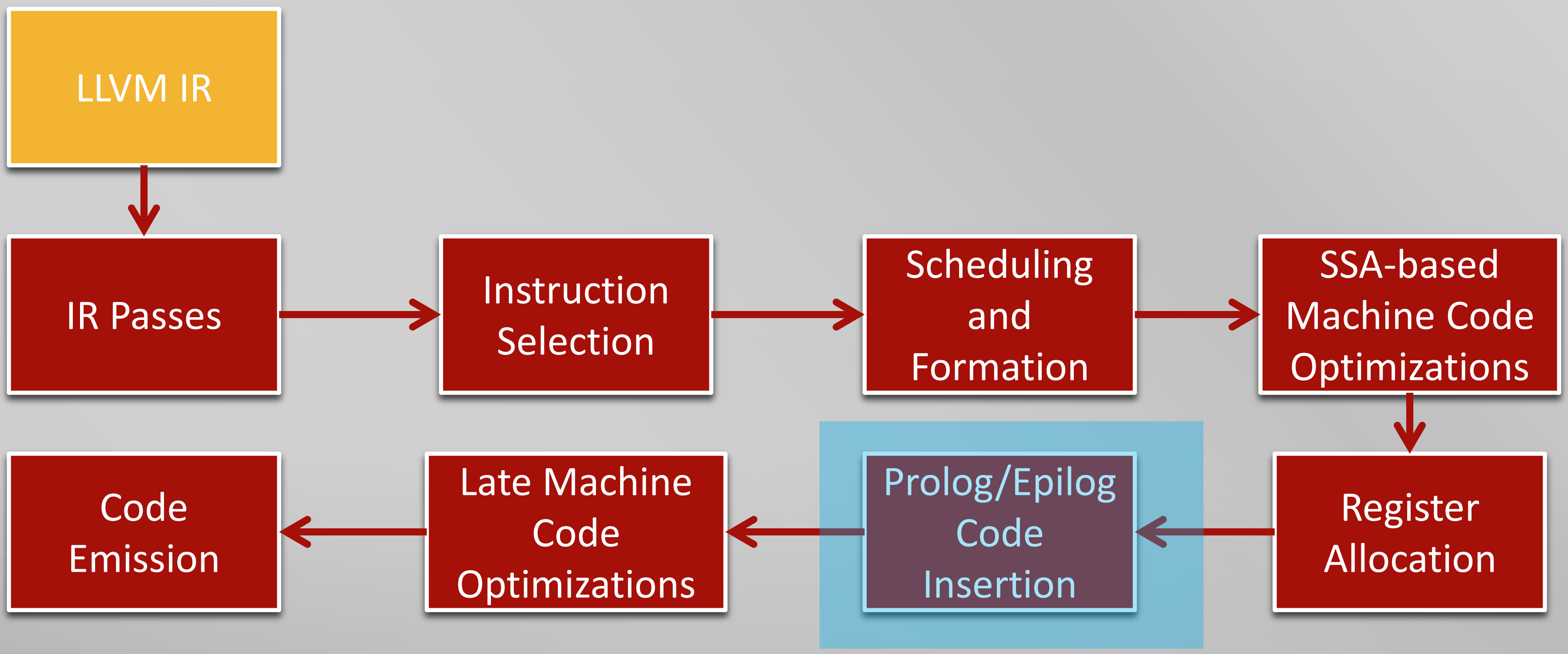
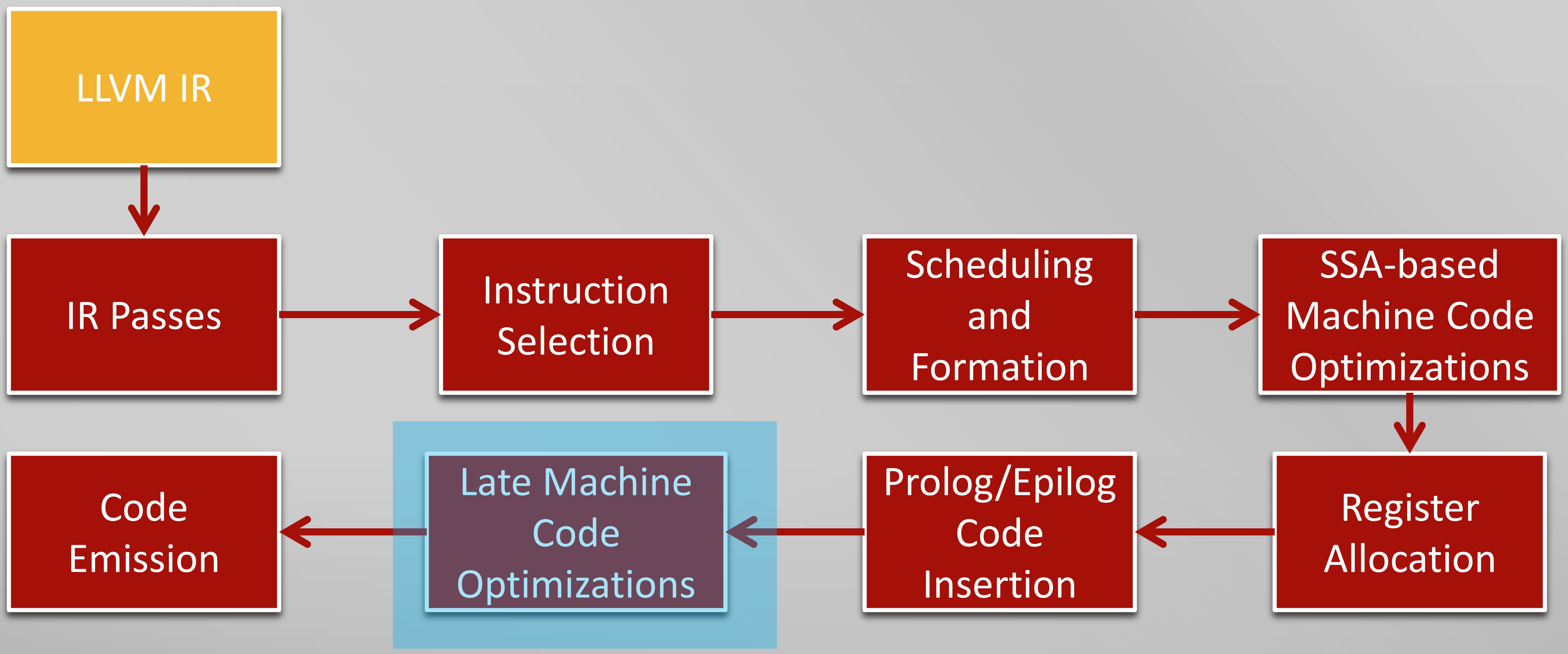


Prolog/Epilog Code Insertion

- At this point the machine code has been generated for functions and the amount of stack pass required is known.
- The compiler inserts the prolog and epilog code for functions.
- Frame-pointer elimination and stack packing optimizations are done here.
- See **lib/Target/TARGETNAME/TARGETNAMEFrameLowering.cpp**

LLVM Infrastructure at a Low Level View

- Where we are next…

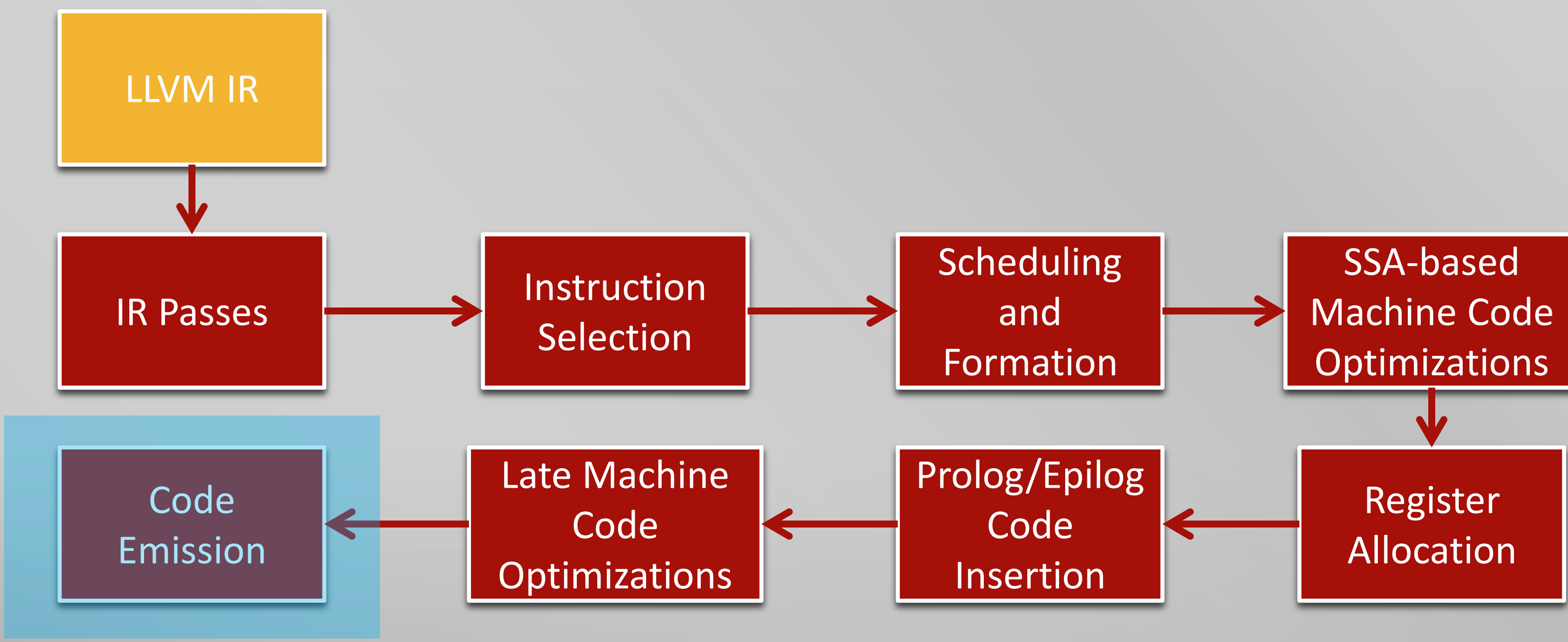


Late Code Optimizations

- Optimizations that operate on the final machine code go here.
- Spill code scheduling and peephole optimizations.
- Implemented by the Target in **lib/Target/TARGETNAME/*** in different files as machine passes.
- This stage is where targets can and have implemented their own **non-SSA based/post-register allocation** machine passes.

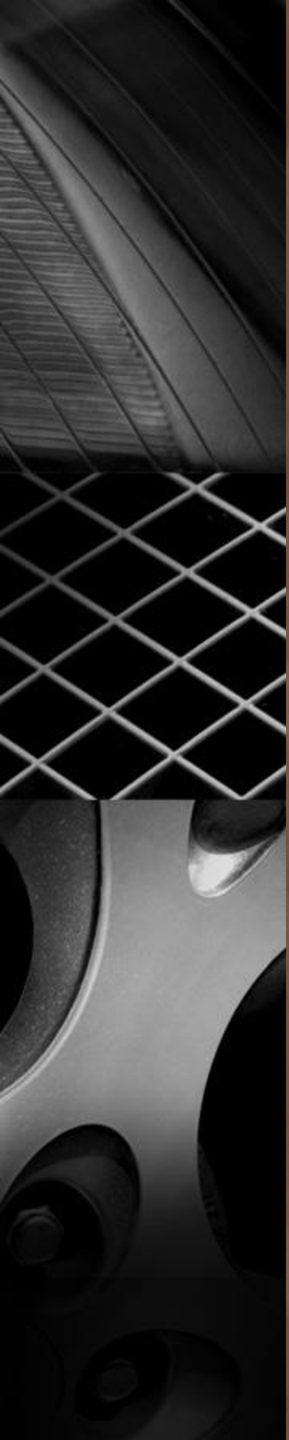
LLVM Infrastructure at a Low Level View

- Where we are next…



Code Emission

- The stage where the code is emitted as either assembly or machine code.
- See **lib/Target/TARGETNAME/TARGETNAMEASMPrinter.cpp** (for asm)
- See **lib/Target/TARGETNAME/TARGETNAMEMCInstLower.cpp** (for obj)
- See **lib/Codegen/TargetLoweringObjectFileImpl.cpp**
- **Etc.**



LLVM Testing

LLVM Testing

- Contains two types:
  - Regression
    - Found under the **test** directory and organized under many different categories.
    - Target specific tests are under **test/CodeGen/TARGETNAME/***
    - Can be run individually using **llvm-lit** or to check all tests run **"make check"**.
  - Whole Program
    - Uses the llvm test-suite.
    - Found in a separate SVN.
    - Programs written in C or C++.
      - Single source, multisource, and external benchmarks (SPEC2000, etc).
    - The suite contains reference outputs of the programs.

Regression Test Format

```
; RUN: llvm-as < %s | llc -march=x86-64 | FileCheck %s

define void @sub1(i32* %p, i32 %v) {
entry:
        ; CHECK: sub1:
        ; CHECK: subl
                %0 = tail call i32 @llvm.atomic.load.sub.i32.p0i32(i32* %p, i32 %v)
                ret void
}
```

Regression Test Format

```
; RUN: llvm-as < %s | llc -march=x86-64 | FileCheck %s

define void @sub1(i32* %p, i32 %v) {
entry:
	; CHECK: sub1:
	; CHECK: subl
		%0 = tail call i32 @llvm.atomic.load.sub.i32.p0i32(i32* %p, i32 %v)
		ret void
}
```

Normal LLVM IR

Regression Test Format

```
; RUN: llvm-as < %s | llc -march=x86-64 | FileCheck %s

define void @sub1(i32* %p, i32 %v) {
entry:
        ; CHECK: sub1:
        ; CHECK: subl
                %0 = tail call i32 @llvm.atomic.load.sub.i32.p0i32(i32* %p, i32 %v)
                ret void
}
```

Check statements that the output generated from the IR checked against.

Regression Test Format

```
; RUN: llvm-as < %s | llc -march=x86-64 | FileCheck %s

define void @sub1(i32* %p, i32 %v) {
entry:
        ; CHECK: sub1:
        ; CHECK: subl
                %0 = tail call i32 @llvm.atomic.load.sub.i32.p0i32(i32* %p, i32 %v)
                ret void
}
```

Run Line.

Close to the end

LLVM Tools

- clang
  - Frontend for c, c++, obj-c, obj-c++.
- llc
  - Backend – i.e. LLVM.
- opt
  - Tool to run and debug passes.
- llvm-lit
  - Tool to run tests.

Building LLVM (and Clang)

1. Choose a wise location for your source since it cannot be moved after compilation.
2. Install g++ and cmake (from a package manager).
3. Checkout LLVM
   - svn co http://llvm.org/svn/llvm-project/llvm/trunk llvm
4. Checkout Clang
   - cd llvm/tools
   - svn co http://llvm.org/svn/llvm-project/cfe/trunk clang
5. Create a build directory (not inside of the src directory)
   - mkdir **build_dir**
   - cd **build_dir**
6. Run cmake from the build directory
   - cmake -DCMAKE_BUILD_TYPE:STRING=Debug **/path/to/llvm/src**
7. Compile
   - make all
   - make check
8. There should now be bin and lib directories (found in the main directory).
   1. Add the **bin** and **lib** directories to your **PATH** and **LD_LIBRARY_PATH** variables.

Explanation about Building LLVM (and Clang)

- Why ‘make all’?
  - We want llvm-lit to run individual tests and other developer tools.
  - Normally the internal **utils** are not built by llvm which means you would manually have to install python modules and tools to get llvm-lit to work.
  - Trust me, you don’t want to have to do that.
- Why ‘make check’?
  - This generates a configuration file for llvm-lit.
  - You technically don’t even need to wait for this command to complete beyond the first few steps.
- Why NOT ‘make install’?
  - None of the *utils* will install and only the stuff needed for running llvm will.
  - So you would need to add the bin and lib directories to your path variables anyway.

What to take away

- A contemporary compiler infrastructure eases programmer burden for newbies and seasoned veterans alike.
- Through providing well-defined mechanisms to
  - Implement new targets (target description (td, c++)).
  - Implement transformations and optimizations (passes).
  - Implement new reg schedulers (register as pass, **see lib/CodeGen/RegAllocBasic.cpp**)
  - Test regressions (llvm-lit) and whole programs (test-suite).
  - Visualize data (CFGs, DAGS, Dom trees).
- Documentation
  - This gives you structure and methodology.
- You can too!

Bibliography

- http://llvm.org/docs/
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- http://llvm.org/pubs/2002-08-09-LLVMCompilationStrategy.html
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- Jürgen Ributzka
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