# Architecture for a Next-Generation GCC

Chris Lattner
sabre@nondot.org

Vikram Adve
vadve@cs.uiuc.edu

http://llvm.cs.uiuc.edu/

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## GCC Optimizer Problems:

- **Scope of optimization is very limited:**
  - Most transformations work on functions…
    - …and one is even limited to extended basic blocks
  - No *whole-program* analyses or optimization!
    - e.g. alias analysis must be extremely conservative
- **Tree & RTL are bad for mid-level opt'zns:**
  - Tree is language-specific and too *high*-level
  - RTL is target-specific and too *low*-level

## New Optimization Architecture:

- **Transparent *link-time* optimization:**
  - Completely compatible with user makefiles
- **Enables sophisticated interprocedural analyses (IPA) and optimizations (IPO):**
  - Increase the scope of analysis and optimization
- **A new representation for optimization:**
  - Typed, SSA-based, three-address code
  - Source language *and* target-independent

# Example Applications for GCC:

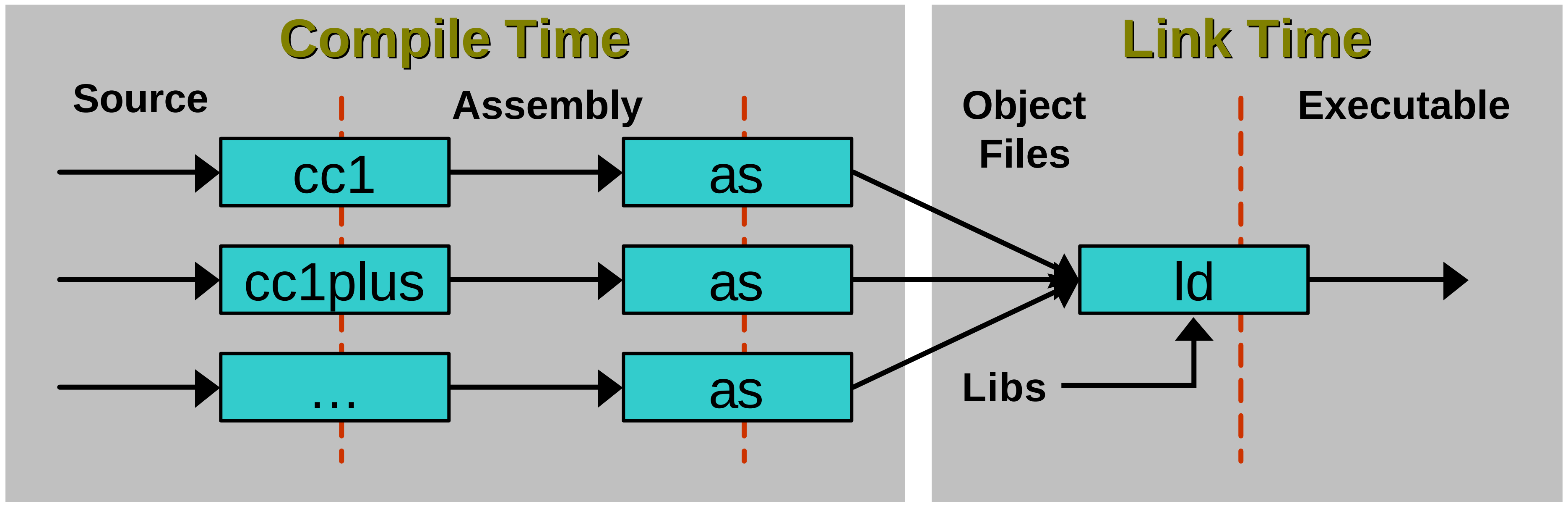
- **Fix inlining heuristics:**
  - Allows whole program, bottom-up inlining
  - Cost metric is more accurate than for trees
- **Improved alias analysis:**
  - Dramatically improved precision
  - Code motion, redundancy elimination gains
- **Work around low-level ABI problems:**
  - Tailor linkage of functions with IP information

## Talk Outline:

- High-Level Compiler Architecture
  - How does the proposed GCC work?
- Code Representation Details
  - What does the representation look like?
- LLVM: An Implementation
  - Implementation status and experiences
- Conclusion

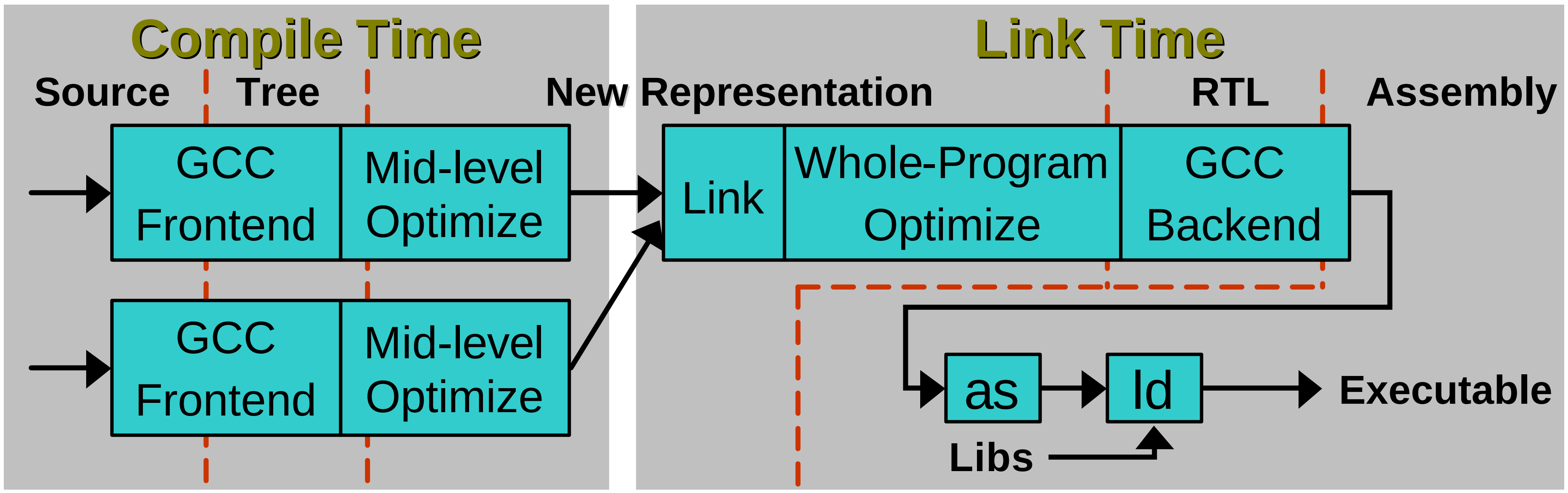
## Traditional GCC Organization:

- **Compile:** source to target assembly
- **Assemble:** target assembly to object file
- **Link:** combine object files into an executable



# Proposed GCC Architecture:

- **Split the existing compiler in half:**
  - Parsing & semantic analysis at compile time
  - Code generation at link-time
  - Optimization at compile-time *and* link-time



## Why Link-Time?

- **Fits into normal compile & link model:**
  - User makefiles do not have to change
  - Enabled if compiling at **`-O4`**
- **Missing code severely limits IPA & IPO:**
  - Must make conservative assumptions:
    - An unknown callee can do just about anything
  - At link-time, most of the program is available for the first time!

## Making Link-Time Opt Feasible:

- **Many commercial compilers support link-time optimization (Intel, SGI, HP, etc…):**
  - These export an AST-level representation, then perform **all** optimization at link-time
- **Our proposal:**
  - Optimize as much at compile-time as possible
  - Perform aggressive IPA/IPO at link-time
  - Allows mixed object files in native & IR format

## No major GCC changes:

- **New GCC components:**
  - New expander from Tree to IR
  - New expander from IR to RTL
  - Must extend the compiler driver
- **Existing code path can be retained:**
  - When disabled, does not effect performance
  - When **`-O2`** is enabled, use new mid-level optimizations a function- (or unit-) at-a-time

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## Code Representation Properties:

- **Low-Level, SSA based, and “RISC-like”:**
  - SSA-based = efficient, sparse, global opt’zns
  - Orthogonal, as few operations as possible
  - Simple, well defined semantics (documented)
  - Simplify development of optimizations:
    - Development & ***maintenance*** is very costly!
- **Concrete details come from LLVM:**
  - More details about LLVM come later in talk

# Code Example:

```
struct pair {
  int X; float Y;
};
void Sum(float *, struct pair *P);

int Process(float *A, int N) {
  int i;
  struct pair P = {0,0};
  for (i = 0; i < N; ++i) {
    Sum(A, &P);
    A++; }
  return P.X;
}
```

Typed pointer arithmetic for explicit access to memory

```
%pair = type { int, float }
declare void %Sum(float*, %pai

int %Process(float* %A.0, int       {
entry:
  %P = alloca %pair
  %tmp.0 = getelementptr %pair* %P, long 0, ubyte 0
  store int 0, int* %tmp.0
  %tmp.1 = getelementptr %pair* %P, long 0, ubyte 1
  store float 0.0, float* %tmp.1
  %tmp.3 = setlt int 0, %N
  br bool %tmp.3, label %loop,
loop:
  %i.1 = phi int [ 0, %entry ]
  %A.1 = phi float* [ %A.0, %ent
                    [ %A.2, %l  op ]
  call void %Sum(float* %A.1, %pair* %P)
  %A.2 = getelementptr float* %A.1, long 1
  %i.2 = add int %i.1, 1
  %tmp.4 = setlt int %i.1, %N
  br bool %tmp.4, label %loop, label %return
return:
  %tmp.5 = load int* %tmp.0
  ret int %tmp.5
}
```

tmp.0 = &P[0].0

A.2 = &A.1[1]

## Strongly-Typed Representation:

- **Key challenge:**
  - Support high-level analyses & transformations
  - ... on a *low-level* representation!
- **Types provide this high-level info:**
  - Enables aggressive analyses and opt’zns:
    - e.g. automatic pool allocation, safety checking, data structure analysis, etc…
  - Every computed value has a type
- **Type system is language-neutral!**

## Type System Details:

- **Simple lang. independent type system:**
  - Primitives: void, bool, float, ushort, opaque, …
  - Derived: pointer, array, structure, function
  - No high-level types!
- **Source language types are lowered:**
  - e.g. `T&` ✍ `T*`
  - e.g. `class T : S { int X; }` ✍ `{ S, int }`
- **Type system *can* be “broken” with casts**

## Full Featured Language:

- **Should contain *all* info about the code:**
  - functions, globals, inline asm, etc…
  - Should be possible to serialize and deserialize a program at any time
- **Language has binary and text formats:**
  - Both directly correspond to in-memory IR
  - Text is for humans, binary is faster to parse
  - Makes debugging and understanding easier!

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## LLVM: Low-Level Virtual Machine

- **A research compiler infrastructure:**
  - Provides a solid foundation for research
  - In use both inside and outside of UIUC:
    - Compilers, architecture, & dynamic compilation
    - Two advanced compilers courses
- **Development Progress:**
  - 2.5 years old, ~130K lines of C++ code
  - First public release is coming soon:
    - 1.0 release this summer, prereleases via email

## LLVM Implementation Status:

- **Most of this proposal is implemented:**
  - Tree ✍ LLVM expander (for C and C++)
  - Linker, optimizer, textual & bytecode formats
  - Mid-level optimizer is sequence of 22 passes
- **All sorts of analyses & optimizations:**
  - Scalar: ADCE, SCCP, register promotion, …
  - CFG: dominators, natural loops, profiling, …
  - IP: alias analysis, automatic pool allocation, interprocedural mod/ref, safety verification…

## Other LLVM Infrastructure:

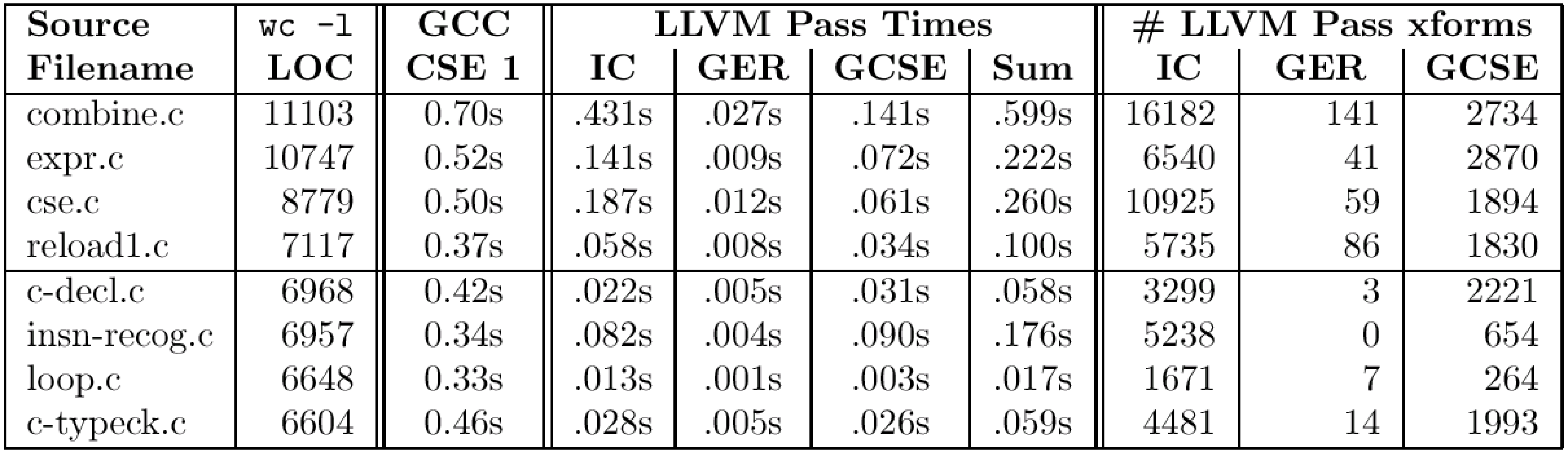
- **Direct execution of LLVM bytecode:**
  - A portable interpreter, a Just-In-Time compiler
- **Several custom (non-GCC) backends:**
  - Sparc-V9, IA-32, C backend
- **The LLVM "Pass Manager":**
  - Declarative system for tracking analysis and optimizer pass dependencies
  - Assists building tools out of a series of passes

## LLVM Development Tools:

- **Invariant checking:**
  - Automatic IR memory leak detection
  - A verifier pass which checks for consistency
    - Definitions dominate all uses, etc…
- **Bugpoint - automatic test-case reducer:**
  - Automatically reduces test cases to a small example which still causes a problem
  - Can debug miscompilations or pass crashes

## LLVM is extremely fast:

- **End-to-end performance isn't great yet:**
  - Not yet integrated into GCC proper
- **But transformations are very fast:**
  - Some example numbers from the paper:



| Source | wc -l | GCC | LLVM Pass Times | | | | # LLVM Pass xforms | | |
|---|---|---|---|---|---|---|---|---|---|
| Filename | LOC | CSE 1 | IC | GER | GCSE | Sum | IC | GER | GCSE |
| combine.c | 11103 | 0.70s | .431s | .027s | .141s | .599s | 16182 | 141 | 2734 |
| expr.c | 10747 | 0.52s | .141s | .009s | .072s | .222s | 6540 | 41 | 2870 |
| cse.c | 8779 | 0.50s | .187s | .012s | .061s | .260s | 10925 | 59 | 1894 |
| reload1.c | 7117 | 0.37s | .058s | .008s | .034s | .100s | 5735 | 86 | 1830 |
| c-decl.c | 6968 | 0.42s | .022s | .005s | .031s | .058s | 3299 | 3 | 2221 |
| insn-recog.c | 6957 | 0.34s | .082s | .004s | .090s | .176s | 5238 | 0 | 654 |
| loop.c | 6648 | 0.33s | .013s | .001s | .003s | .017s | 1671 | 7 | 264 |
| c-typeck.c | 6604 | 0.46s | .028s | .005s | .026s | .059s | 4481 | 14 | 1993 |

## Conclusion:

- **Contributions:**
  - A realistic architecture for an aggressive link-time optimizer
  - A representation for efficient and powerful analyses and transformations
- **LLVM is available…**
  - … and we appreciate your feedback!

**`http://llvm.cs.uiuc.edu`**