The Theory, History and Future of System Linkers

Luba Tang
CEO & Founder, Skymizer Inc.

Outline

- **The History**
  - Target Independent Linkers
  - Post Optimizers
  - Instrumentation Tools
- **The Theory**
  - Linking Language
  - Fragment-reference graph
- **The Future**
  - for GPGPU; for virtual machines
  - The bold project

唐文力 Luba Tang

CEO & Founder of Skymizer Inc.

Architect of MCLinker and GYM compiler

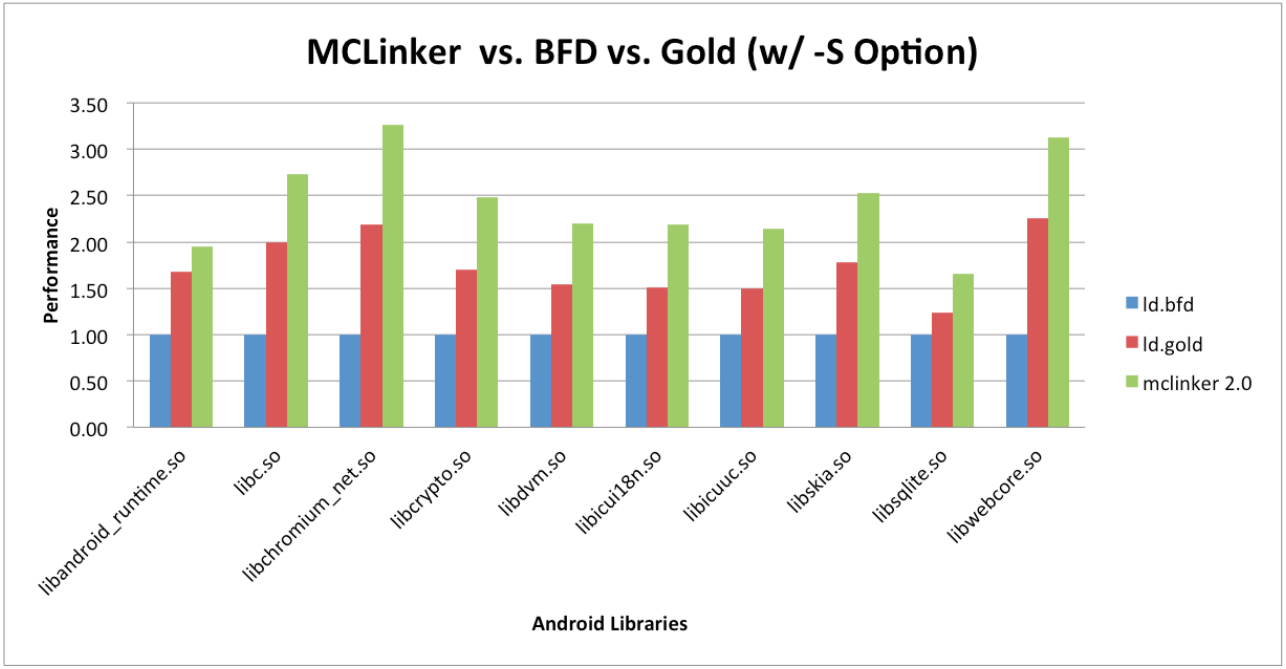
Compiler and Linker/Electronic System Level Design

Linker: The Elephant in the Room

- **System linkers are very complicated.** Only a few team can make a full-fledge system linker.
  - There are only four open source linkers that can be said full-fledge.
    - GNU ld, Google gold can link Linux kernel
    - Apple ld64 can link Mac OS X and iOS
    - MCLinker can link BSD and Android system
- **ELF linkers are super complicated.** There are many undocumented behaviors and target-specific behaviors.
  - The other linkers are developed for more than three years and can not be released. The linking problem is intricate.
- Although a lot of researches have proven linker itself can optimize programs at a high performance level, developers still not get benefit from these researches.

No Linker Really Optimize Programs

- MCLinker is 35% faster than the Google gold, and the Google gold is ~200% faster than GNU ld
- If we turn on optimization flags, the output quality is almost identical to all linkers (<3 %)

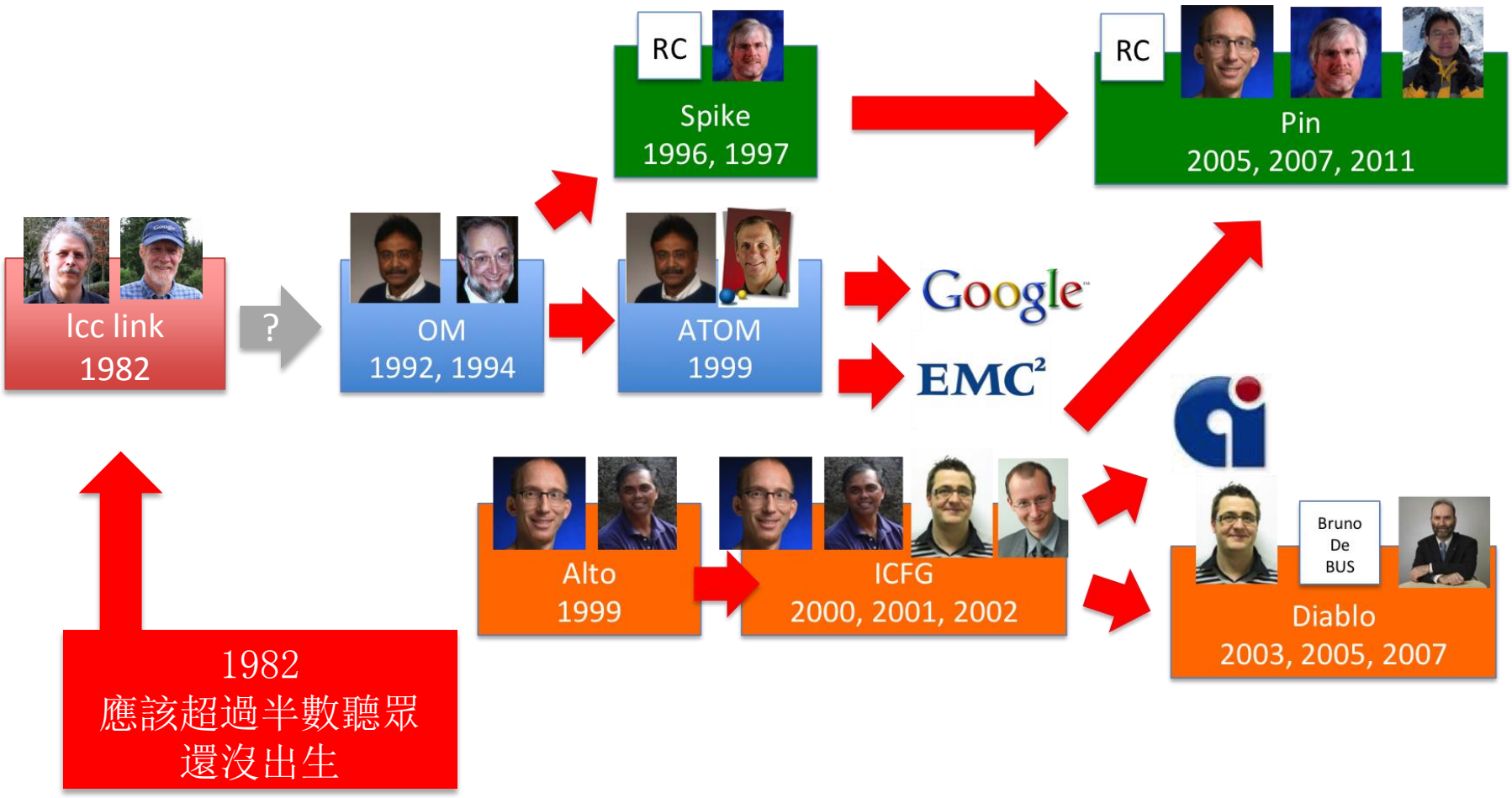


Comparison of ELF Linkers

	GNU ld	Google gold	MCLinker
License	GPLv3 Cannot be adopted by Android		UIUC BSD-Style
Target Platform	All Linux mainstream devices	ARM, X86, X86_64, (Mips, SPARC)	All Android d[illegible]s. ARM[illegible]4 and
Object Format	COFF, a.out, ELF		[illegible]xtensible
Line of Code	500+K		50+K
Performance		Fast	Fastest Steadily x2 than GNU ld, x1.3 than Google gold
Intermediate Representation	The BFD library for reference graph	None	Command line language and reference graph

People Keep Eyes on **Target Independent Linkers**

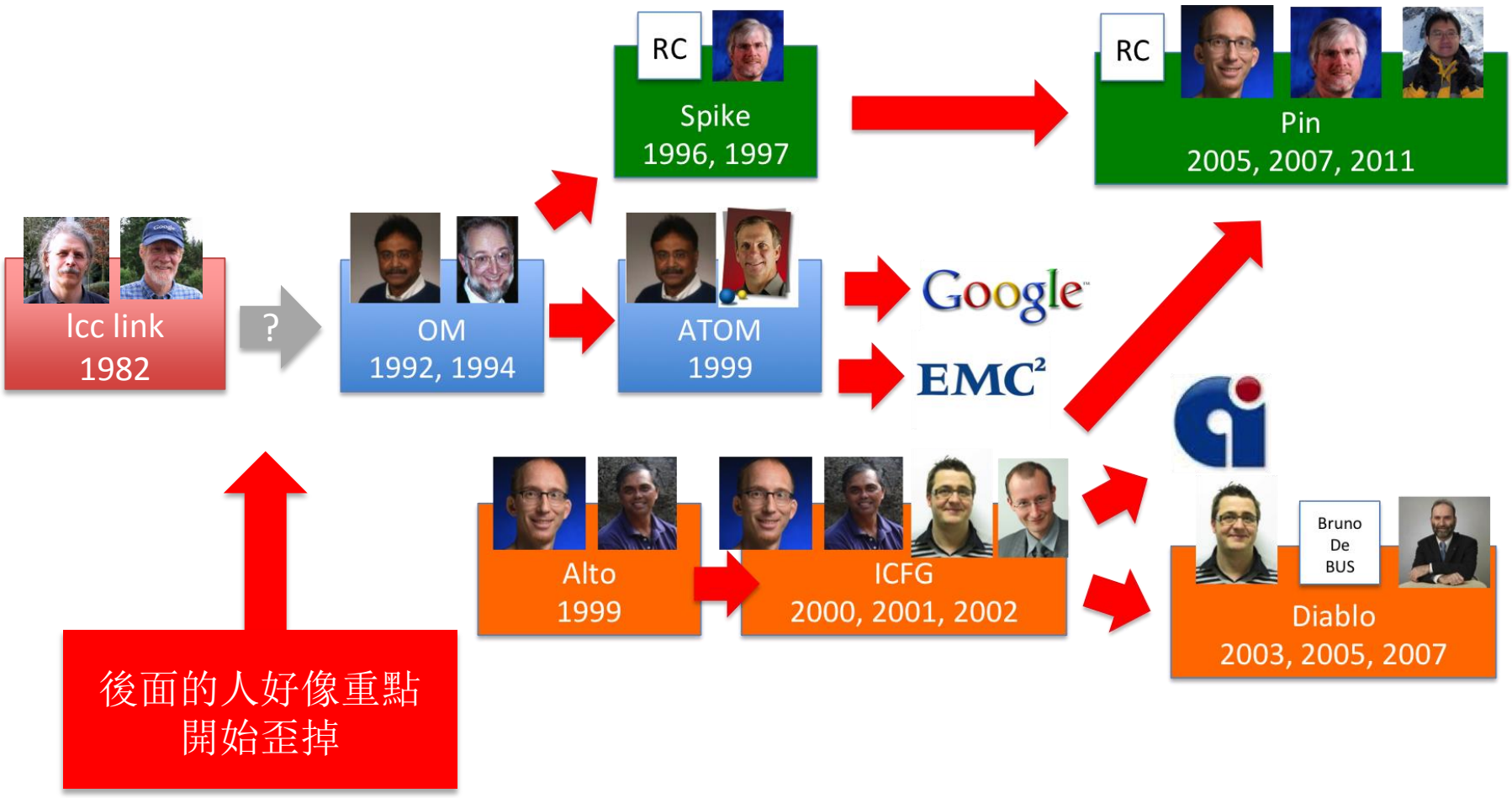
The Most-Recently Important Target Independent Linker Research



LINK: A Machine-Independent Linker

- Team
  - Christopher W. Fraser
  - David R. Hanson
- 1982, Software Practice and Experience
  - Define linker and object language (the predecessor of linker script)
  - Define three basic rules
    - Define the condition of resolution
    - Define the condition of absolute objects
    - Define when to pull in a library

Linker; Post Optimizer; Instrumentation



OM: Code Optimization at Link-Time System

- Team
  - Amitabh Srivastava
  - David W. Wall
- 1992 Technical Report
  - An approach to transform binary into RTL
  - Use RTL to do inter-procedural optimization (5%~14%, SPEC)
    - Dead code elimination
    - Loop Invariant Code Motion (LICM)
- 1994 SIGPLAN (3.8%, SPEC)
  - Replace load instruction and eliminate GAT
  - Reduce code size by 10% or more

OM: Code Optimization at Link-Time System

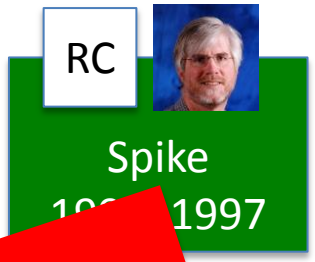
- Key Contributions of OM are
  - OM identifies the problems to translate binary back to assembly.
    - PC-relative branches only
    - Convert jump table back to case-statement
    - No delayed branch, no delay slot

OM
1992, 1994

退休 Ya!

Spike: A successor or a competitor of OM

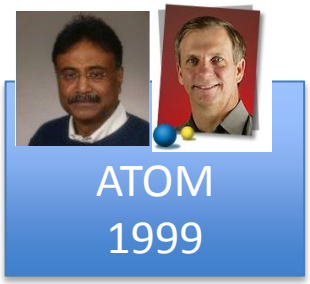
- DEC Team
  - Robert Cohn
  - David W. Goodwin
  - P. Geoffrey Lowney
- 1996 Micro 29 (Th… …olves another OM…
  - Hot … …zation to use shorter jump
  - Work… …on Windows/NT Digital Alpha 3~8% improvement



Finally, someone find some optimization that **can not be done in compiler**

ATOM: Analysis Tools with OM (Best of PLDI 1979-1999)

- Dream Team - 1999
  - Amitabh Srivastava (President of EMC)
  - Alan Eustace (Senior VP of Google Search)



Google

EMC²

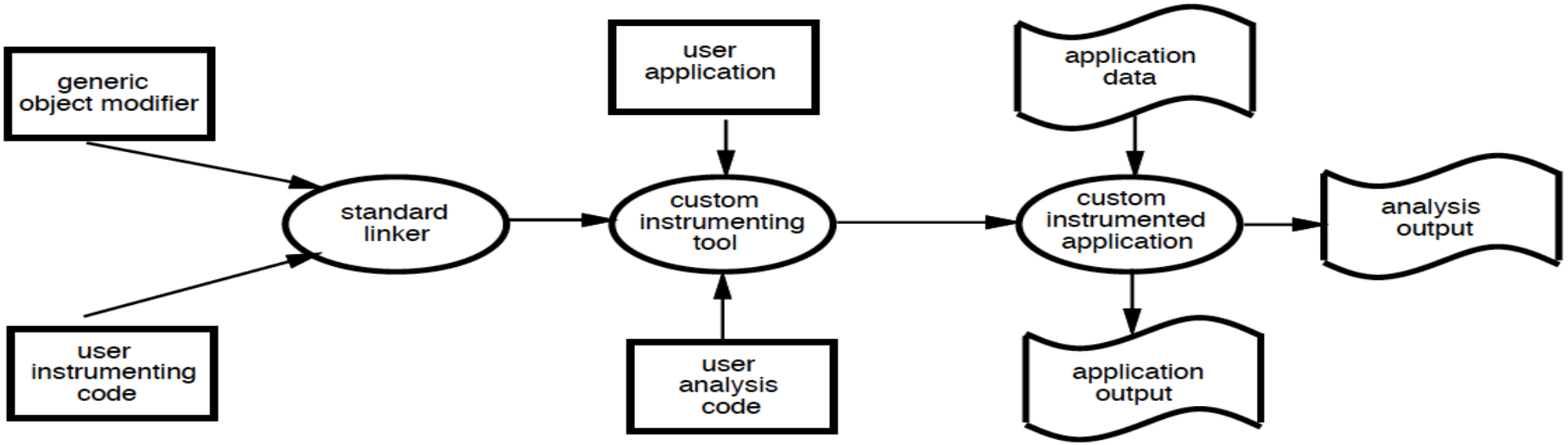
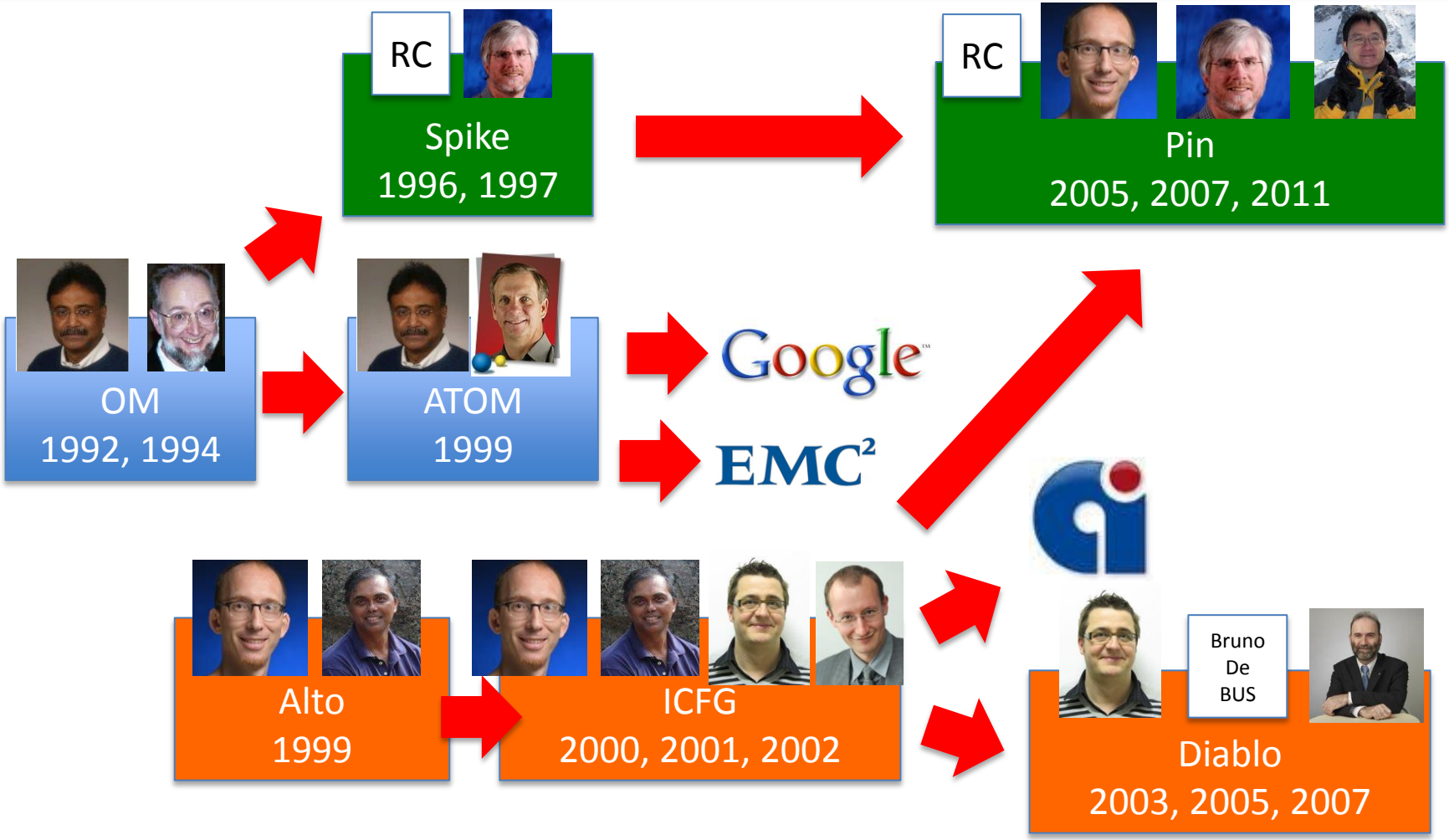


Figure 1: The ATOM Process

ATOM: Analysis Tools with OM (Best of PLDI 1979-1999)

- Key Contributions of ATOM are
  - ATOM defines the use scenario and APIs of an instrumentation tool
  - Intel Pin follows APIs of ATOM.
- The rest contributions:
  - Reducing procedure call overhead (caller-save and callee-save)
  - Use virtual machine to instrument program
    - Defines the necessary memory layout

Chronicle of Linker Optimization



Alto: A Link-Time Optimizer for the Compaq Alpha

- Team
  - Robert Muth
  - Saumya Debray
  - Scott Watterson
  - Keo De Bosschere
- Convert binary into control flow graph
  - General approach
  - The inspirer of ICFG

Alto: A Link-Time Optimizer for the Compaq Alpha

- Powerful Analysis and Optimization
  - Simplification
    - Dead code elimination
    - Normalize operations who express the same semantics
    - Use nops instead of remove instructions direct
  - Analysis
    - Machine level idioms for co
    - Live analysis (regist
  - Optimizatio
    - C ove load, 6.4%)
    - De ution
    - Unu emory elimination (remove load, speed up 5.7%)
    - Low level inlining (10% on average)
    - Profile-directed code layout (6.5%)
    - Instruction scheduling

There are a lot of performance hidden in linkers

ICFG: Interprocedural Control Flow Graph

- Team
  - Saumya Debray
  - William Evans
  - Robert Muth
  - Daniel Kastner
  - Bjorn De Sutter
  - Koen De Bosscher
- ACM Trans… …g Languages and Systems
  - Define… …G
  - Collect compiler techniques for code compaction
  - Reduce 30% on the average

Post optimizer - Not a functional linker

Diablo: Post-Pass Optimization

- Team, Collection of Euro
  - Bruno De Bus
  - Saumya Debray
  - William Evans
  - Robert Muth
  - Daniel Kastner
  - Ludo Van Put
  - Bjorn De Sutter
  - Koen De Bosschere

- First complete post-pass optimizer
  - A lot of following researches

Diablo: Post-Pass Optimization

- For code size, C++ have more opportunity than C
  - Sifting out the Mud: Low Level C++ Code Reuse, OOPSLA'02
    - Reduce 27~70%, 43% on average
  - Combining Global Code [illegible], LCTES'01
    - Reduce [illegible]
- CFG re[illegible]on becomes mature
  - Gener[illegible]ontrol Flow reconstruction from Assembly Code, LCTES'02
  - Can handle delay slots and restricted indirection

Still Post optimizer - Not a functional linker
Limited in static object files

Pin: Building Customized Program Analysis Tools with Dynamic Instrumentation

- Team, Collection of USA, Intel
  - Chi-Keung Luk
  - Robert Cohn
  - Robert Muth
  - Harish Patil
  - Artur Klauser
  - Geoff Lowney
  - Steven Wallace
  - Vijay Janapa Reddi
  - Kim Hazelwood
- Pin release the power of program analysis
  - 1608 citation since 2005
  - Heavily cited in GPGPU and HSA area

Pin: Building Customized Program Analysis Tools with Dynamic Instrumentation

State-of-Art instrumentation tool

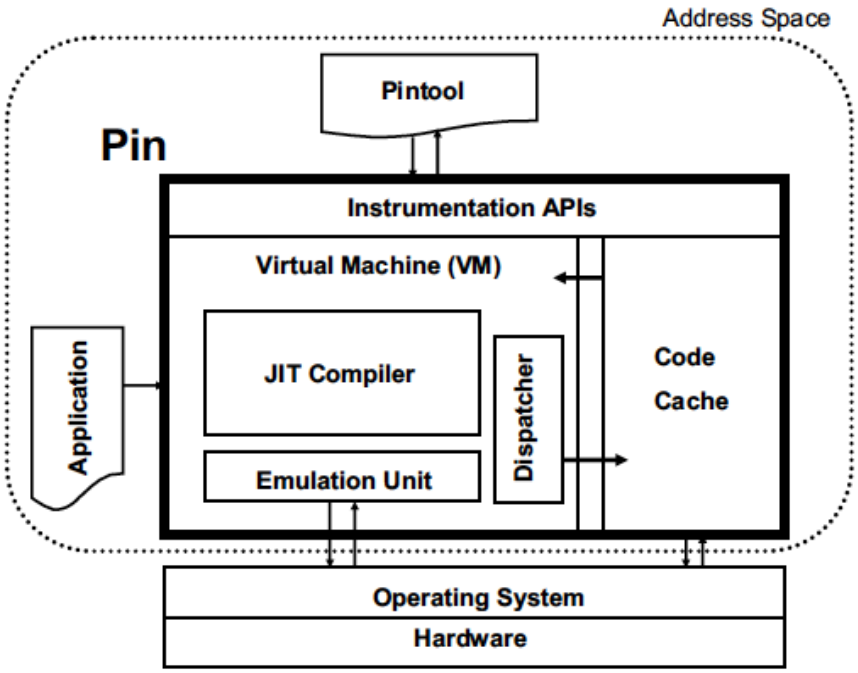


Figure 2. Pin's software architecture

Pin Provides ATOM-like APIs

- User can write his own instrument and analysis code

```
FILE * trace;

// Print a memory write record
VOID RecordMemWrite(VOID * ip, VOID * addr, UINT32 size) {
    fprintf(trace,"%p: W %p %d\n", ip, addr, size);
}

// Called for every instruction
VOID Instruction(INS ins, VOID *v) {
    // instruments writes using a predicated call,
    // i.e. the call happens iff the store is
    // actually executed
    if (INS_IsMemoryWrite(ins))
        INS_InsertPredicatedCall(
            ins, IPOINT_BEFORE, AFUNPTR(RecordMemWrite),
            IARG_INST_PTR, IARG_MEMORYWRITE_EA,
            IARG_MEMORYWRITE_SIZE, IARG_END);
}

int main(int argc, char *argv[]) {
    PIN_Init(argc, argv);
    trace = fopen("atrace.out", "w");
    INS_AddInstrumentFunction(Instruction, 0);
    PIN_StartProgram(); // Never returns
    return 0;
}
```


This is NOT linker
Warner Bros

Linker: The Elephant in the Room

- Although a lot of researches have proven linker itself can optimize programs at a high performance level, developers still not get benefit from these researches.

Outline

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Introduction to Linker Intermediate Representation

- MCLinker is the first *ELF linker to provide an intermediate representation (IR) for efficient transformation and analysis
- MCLinker provides IR on two levels
  - Linker Command Line Language
  - Fragment-Reference Graph
- Fragment is the basic linking unit, it can be
  - A section (coarse granularity)
  - A block of code or instructions (middle granularity)
  - An individual symbol and its code/data (fine granularity)
- MCLinker can trade linking time for the output quality.
  - The finer granularity,
    - Fast, smaller program
    - Longer link time

* Nick Kledzik invents the Atom IR in ld64 for MachO. ld64 inspires MCLinker IRs

The Linker Command Line Language

- Linker's command line options is a kind of language
  - The meaning of a option depends on
    - their positions
    - the other potions
  - Some options have its own grammar

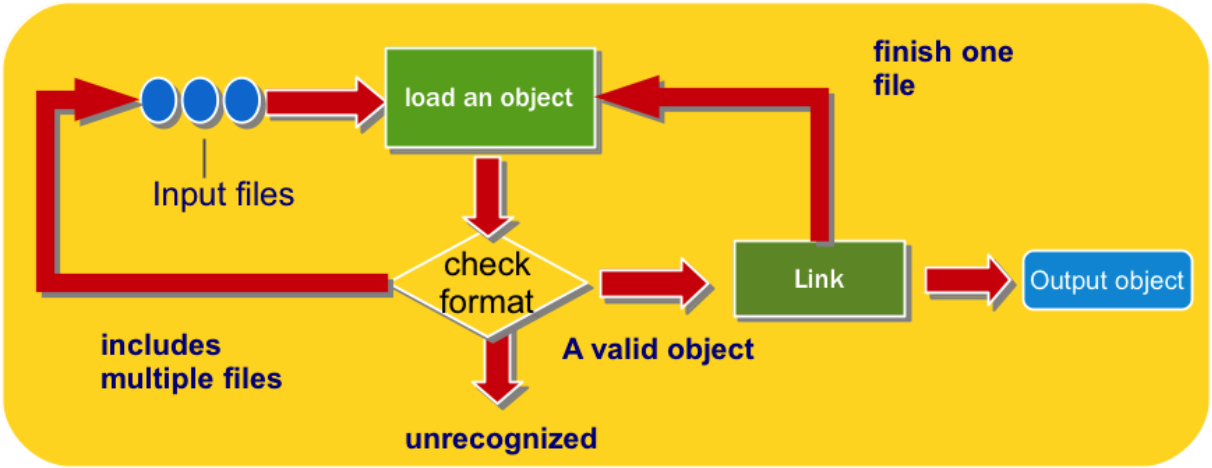
- **Four categories of the options**
  - Input files
  - Attributes of the input files
  - Linker script options
  - General options

- **Examples**

```
ld /tmp/xxx.o -lpthread
ld -as-needed ./yyy.so
ld -defsym=cgo13=0x224
ld -L/opt/lib -T ./my.x
```

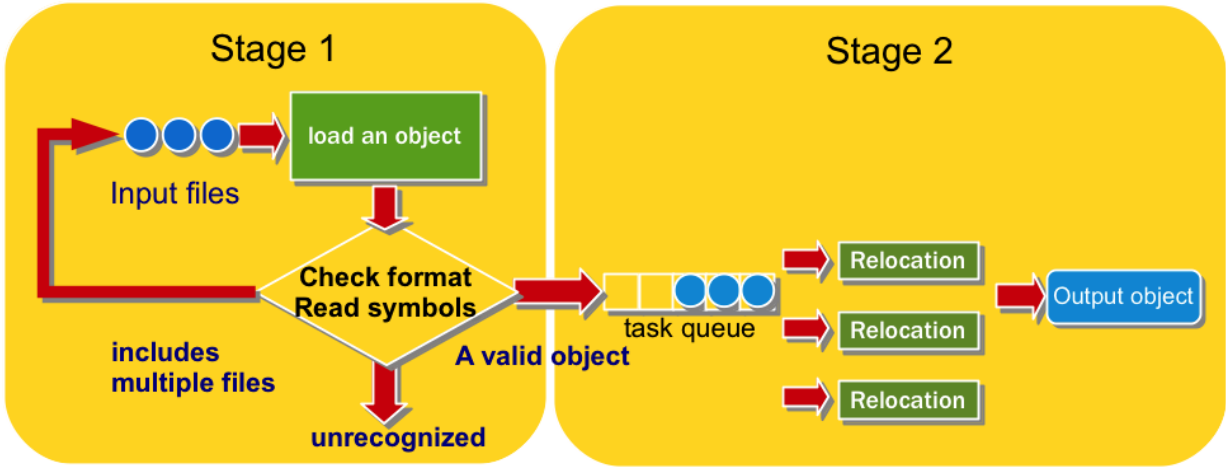
The GNU ld Linker

- The GNU ld linker is an interpreter of the command line language
  - Processing is recursive.
  - No clear separation between individual steps
  - Binary File Descriptor (BFD) is the only IR



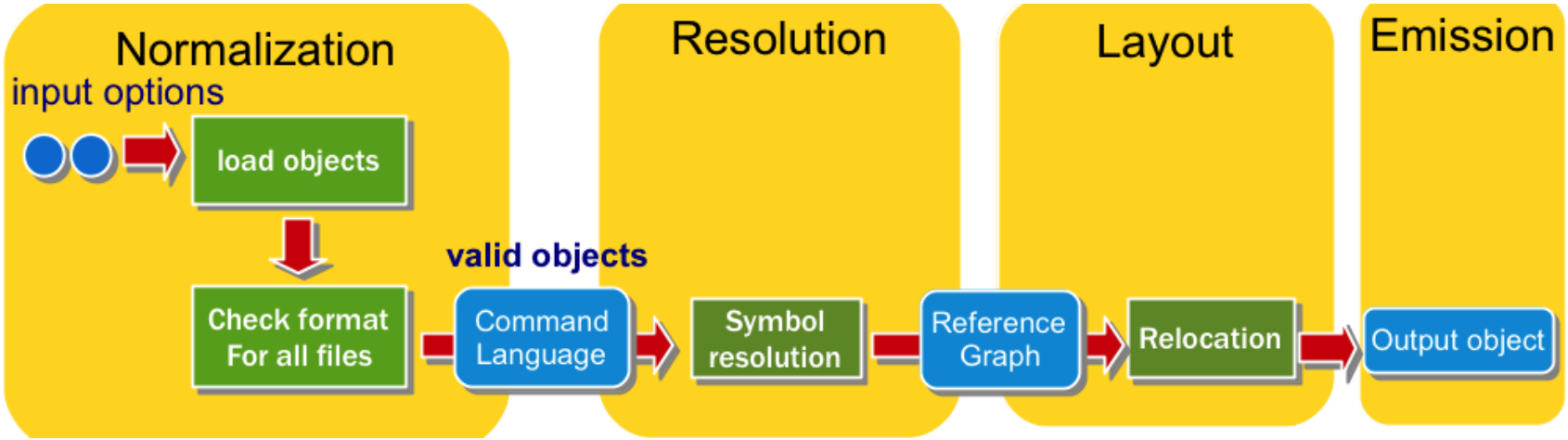
The Google gold Linker

- The Google gold linker separates linking into two stages
  - Symbol resolution
  - Relocation of instructions and data
- Although it has separated the linking processes, it does not provide reusable IR for optimization and analysis
- The Google gold linker illustrates an efficient linking algorithm
  - It's x2 faster than the GNU ld linker
  - Support multiple threads. Appropriate to cloud computing



MCLinker

- MCLinker separates the linking into four distinct stages
  - Normalization – parse the command line language
  - Resolution – resolve symbols
  - Layout – relocate instructions and data
  - Emission – emit file by various formats
- MCLinker provides two level intermediate representation (IR)
  - The command line language level
  - The reference graph level



Input Files on The Command Line

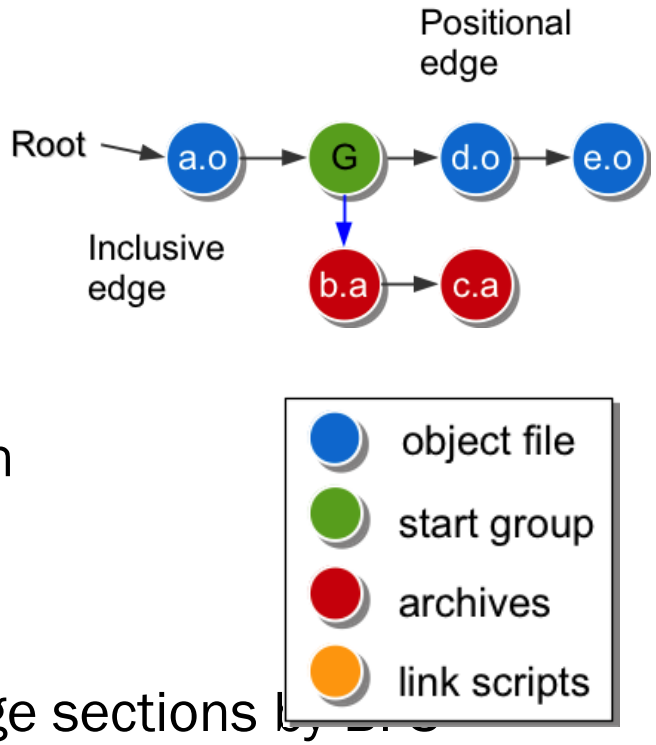
- An input file can be an object file, an archive, or a linker script
- Some input files can be defined multiple times
- The result of linking depends on the positions of inputs on the command line.
  - *Weak symbols* are first-come-first-served
  - COMDAT sections are first-come-first-served
- Two semantics to read input files
  - INPUT(file1, file2, file3, …)
  - GROUP(archive1, archive2, archive3, …)
- Archives in a group are searched *repeatedly* until no new undefined references are created

```
$ ld  a.o –start-group b.a c.a –end-group d.o e.o
```

The Input File Tree

- We can represent the input files on the command line by a tree structure
  - Vertices describes input files and groups on the command line
    - Object files
    - Archives
    - Linker scripts
    - Entrances of groups
- Edges describe the relationships between vertices
  - Positional edges
  - Inclusive edges
- Linkers resolve symbols by DFS and merge sections by DFS
- Example

  $ ld a.o –start-group b.a c.a –end-group d.o e.o



Attributes of Input Files

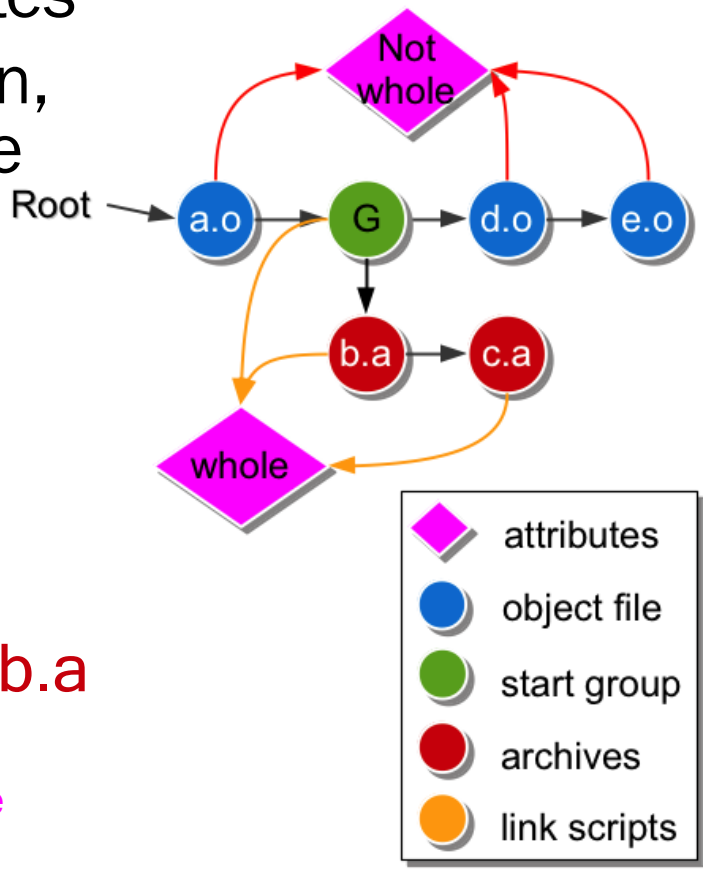
- Attributes change the way that a linker handles the input files
- Attributes affect the input files after the attribute options

Functions	Options	Meanings
Whole archives	--whole-archive	Includes every file in the archive
Link against dynamic libraries	-Bdynamic	Search shared libraries for -l option
As needed	--as-needed	Only add the necessary shared libraries to resolve symbols
Input format	--format=	The format of the following input files

Attributes in The Input File Tree

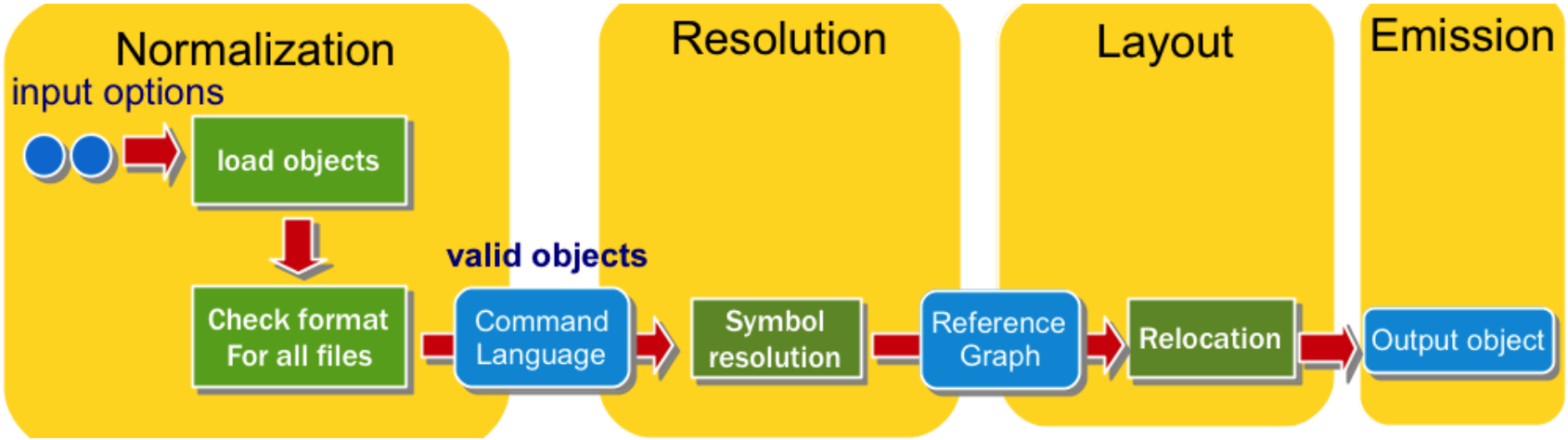
- Every input has a set of attributes
- In the MCLinker implementation, we give every vertex a reference to its attribute set
- If two vertices have identical attributes, they can share a common attribute set.
- Example

```
$ld ./a.o --whole-archive
                    --start-group ./b.a
./c.a --end-group
                    --no-whole-archive
                ./d.o ./e.o
```



Normalization

- Transform the command line language into the input file tree
  - Parse command line options
  - Recognize input files to build up sub-trees
  - Merge all sub-trees to a form the input file tree

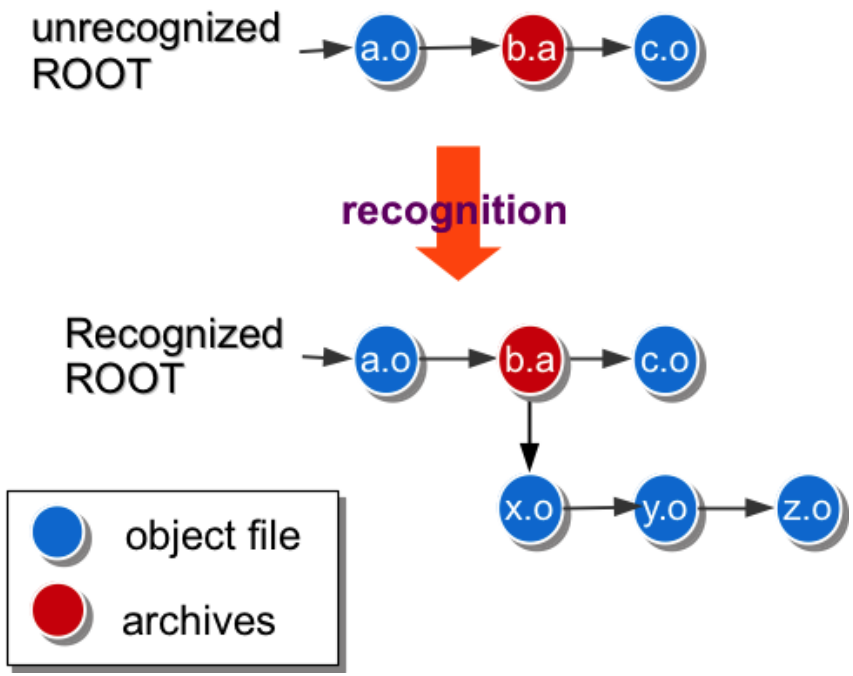


Steps of Normalization

- Step of normalization
  1. Parse the command line options
  2. Recognize archives and linker scripts
  3. Read the linker scripts and archives to create sub-trees
  4. Merge all sub-trees

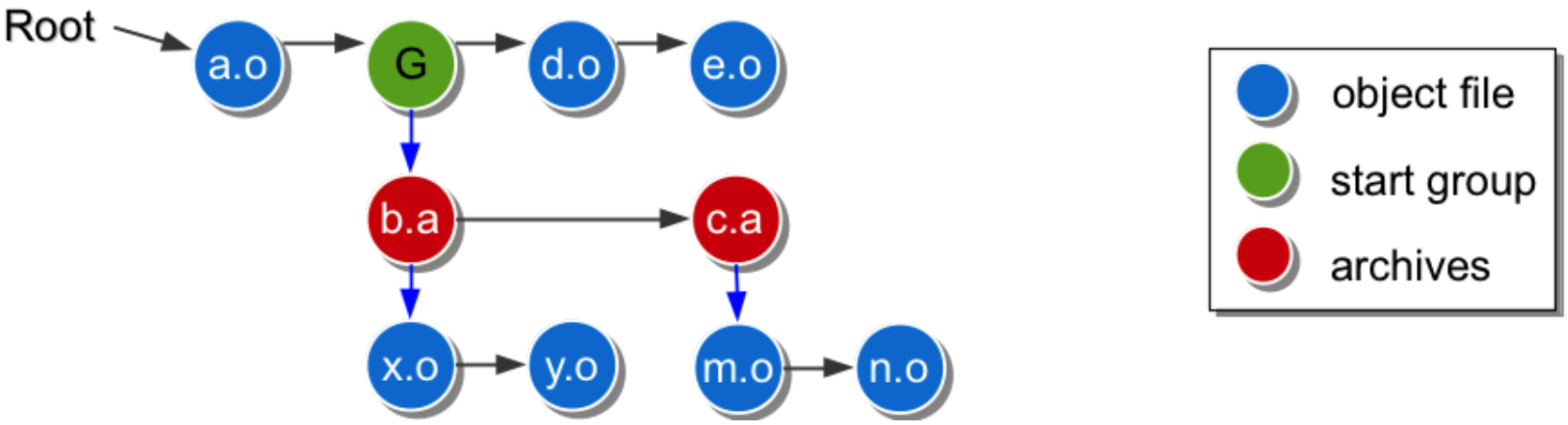
- Example

  $ ld ./a.o ./b.a ./c.o



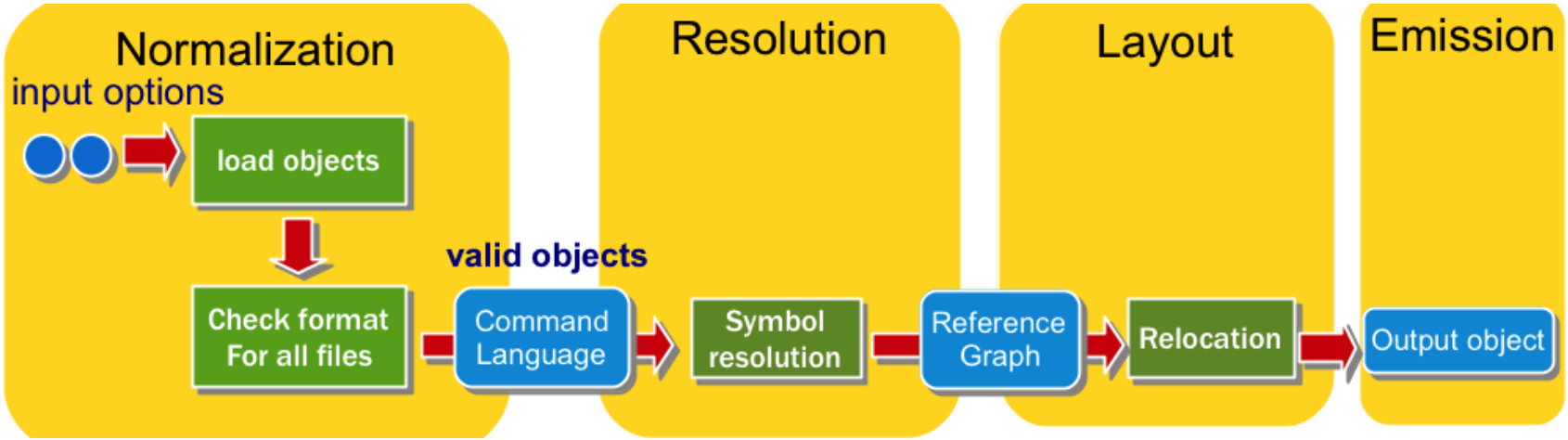
Traverse the Input File Tree

- MCLinker provides different iterators for different purposes
  - For symbol resolution
    - Depth first search for correctness
  - For section merging
    - Breadth first search for cache locality of the output file



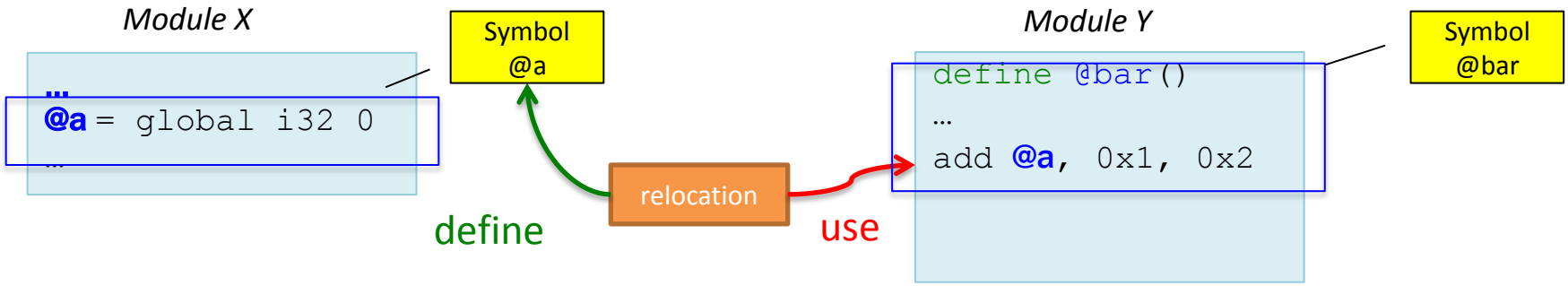
Resolution

- Transform the input file tree into the reference graph
  - Resolves symbols
  - Reads relocation
  - Builds the reference graph



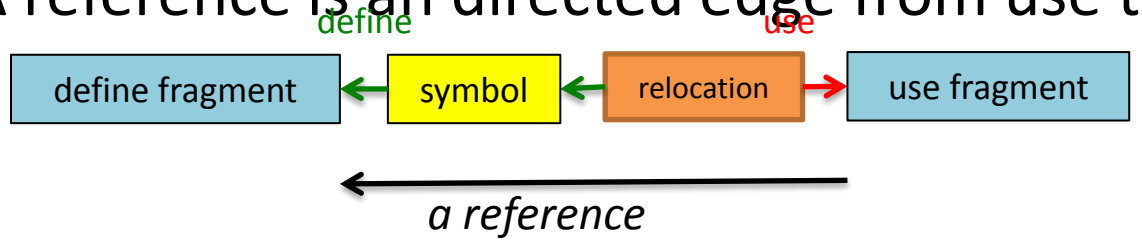
Symbols and Relocations

- A **fragment** is a block of instruction code or data in a module
  - A fragment may be
    - a function,
    - a label (Basic block),
    - a 32-bit integer data, and so on.
- A defined symbol indicates a fragment
- A relocation represents an use-define relationship between two fragments



Fragment-Reference Graph (1/2)

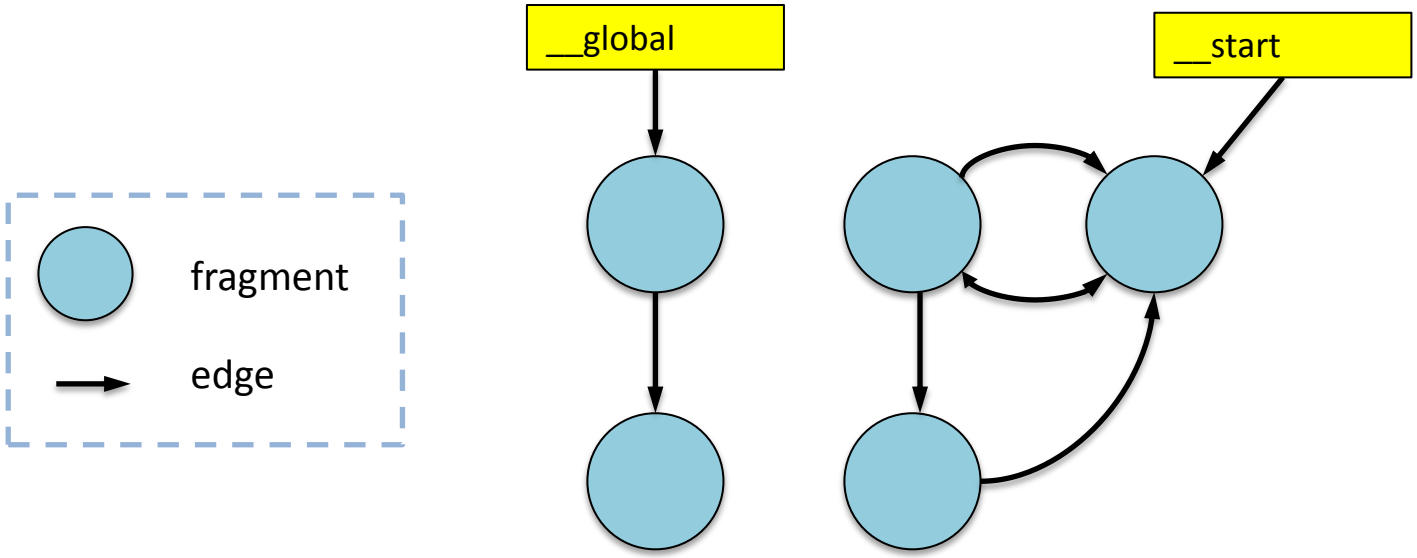
- A reference is a symbolic linkage between two fragments
  - A reference is an directed edge from use to define



- MCLinker represents the input modules as a graph structure
  - Vertices describe the fragments of modules
  - Edges describe the references between two fragments

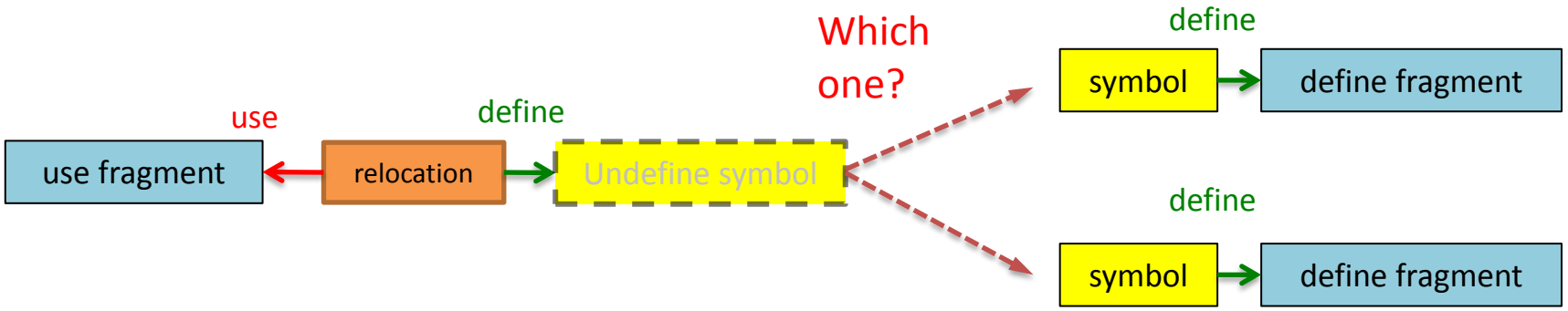
Fragment-Reference Graph (2/2)

- A Fragment-Reference Graph is a digraph, FRG = (V, E, S, O)
  - V is a set of fragments
  - E is a set of references, from use to define
  - S is a set of define symbols. They are the entrances of the graph
  - O is a set of exits and explains later.



Symbol Resolution

- Determine the topology of the reference graph
  - Relocation is a plug
  - Define symbol is a slot
  - Symbol resolution connects plugs and slots.
- Symbols has a set of attributes to help linkers determine the correct topology

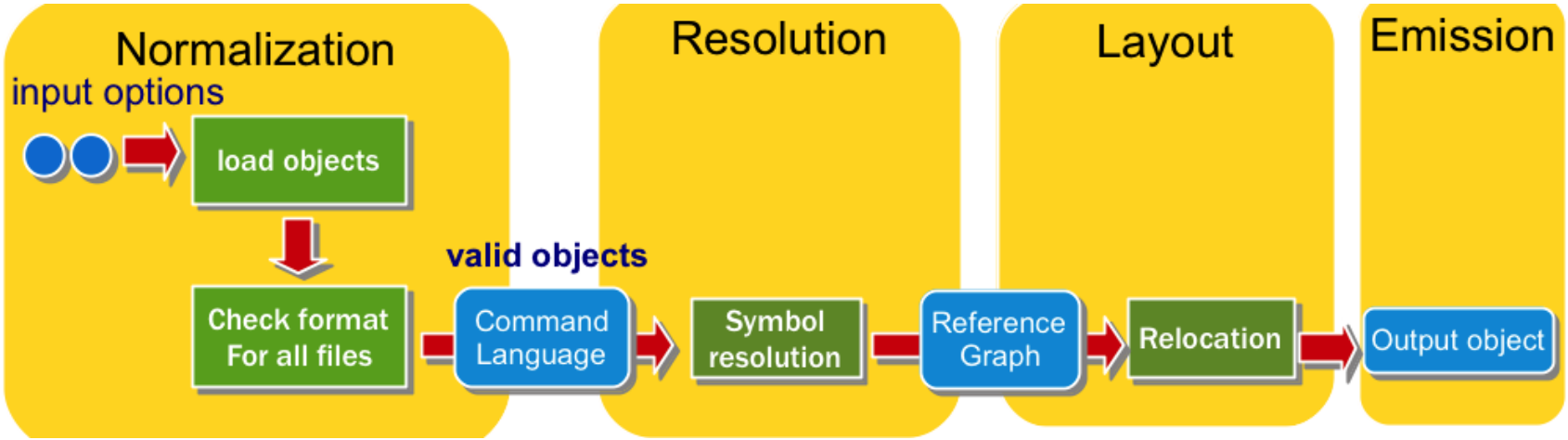


Optimizations on the Fragment-Reference Graph

- Fragment stripping
  - Remove unused fragment for shrink code size (Reachability problem)
  - Traditional linkers strip coarse sections. But MCLinker can strips finer-grained fragments.
  - The finer granularity, the smaller code size
- Branch optimization
  - Replace high cost branch by low cost branch
  - Optimizing by change of the relocation type
- Low-level inlining - ICF
- Fragment duplication for TLS optimization and copy relocations

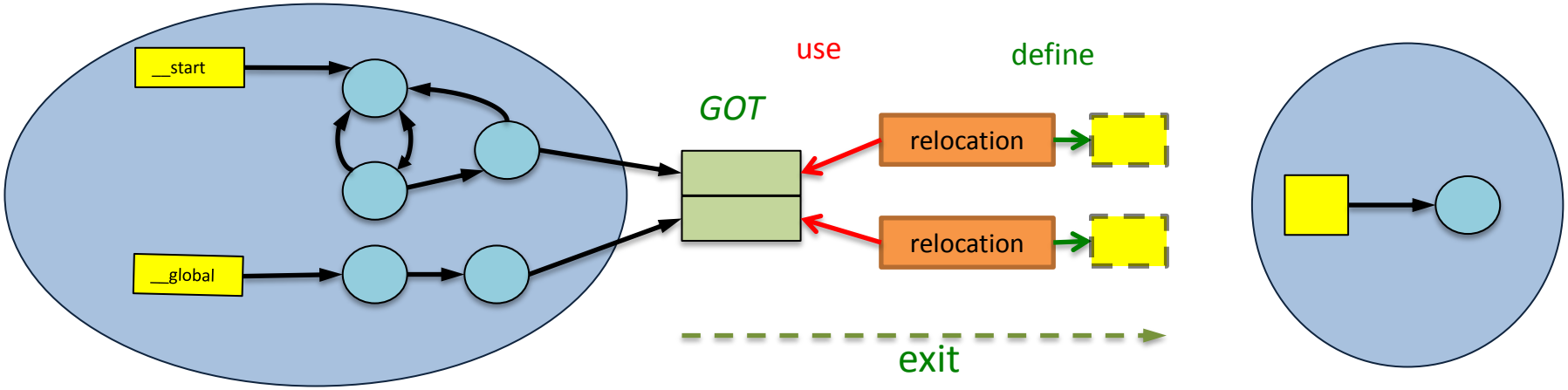
Layout

- To serialize the reference graph into a address space
  - Scan relocations
  - Layout
  - Apply relocations



Exits of The Fragment-Reference Graph

- A Fragment-Reference Graph is a digraph, FRG = (V, E, S, O)
  - O is a set of exits. An exit represents a dynamic relocation to GOT.
  - Represent to access external variables or to call an external function exits the FRG
- If the defining fragment is in an external module, then MCLinker will add exits for the references to the outside module.
  - We have no way to know the memory address of the external module until the load time
  - We add the Global Offset Table (GOT) for the unknown addresses
  - We add dynamic relocations for all entries of the GOT
  - Loader will apply the dynamic relocations and set the correct address in the GOT.
  - The program use the GOT to accesses the external module indirectly



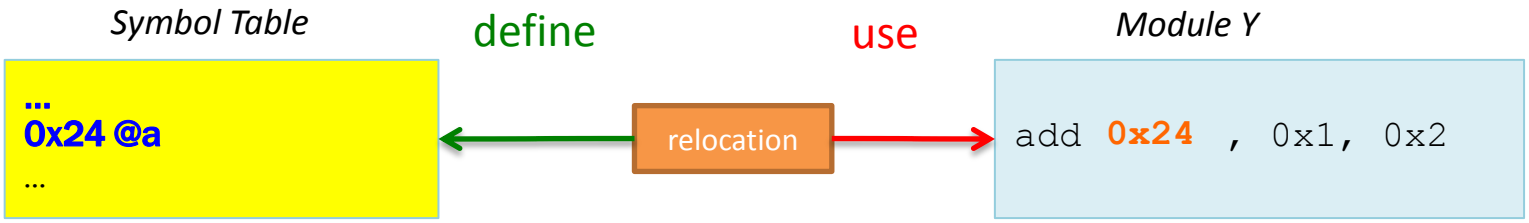
Layout

- Layout is a process to finalize the address of fragment and symbols
  - Sorts FRG=(V, E, S, O) topologically
  - Assigns addresses to {V, S, O}
- Before layout, we must calculate the sizes of all elements of the graph
  - **Relocation scanning**
    - Reserve exits and calculate the sizes of all exits
    - Undefined global symbol, GOT, and dynamic relocations
  - ***Pre-layout**
    - Calculate the size of all fragments
    - Calculate the size of all entrances
      - Global symbols and the hash table

* MCLinker follows the Google gold linker's naming. But pre-layout is opaque and may be renamed.

Apply relocation (1/2)

- Adjusts the content of using fragments
  - Final addresses of symbol is known after layout
  - Correct use fragment by accessed address

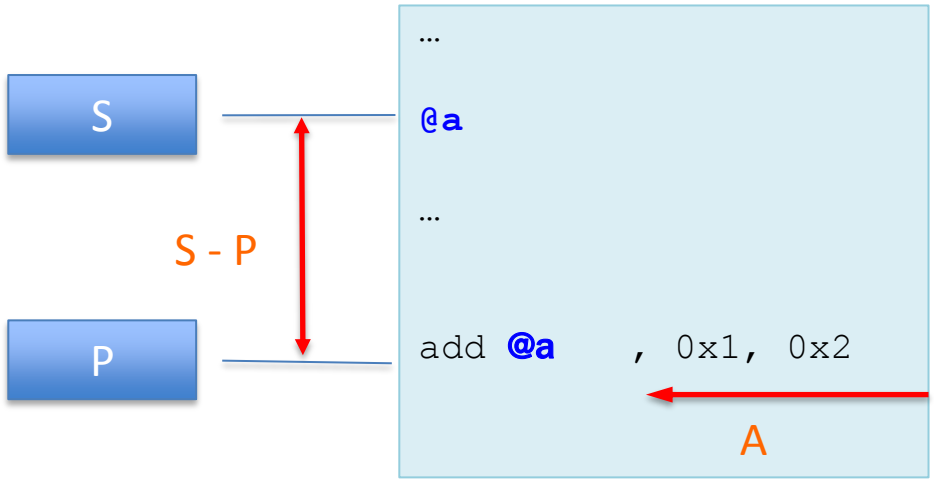


Apply relocation (2/2)

- Replaces absolute addresses by PC-related offset if supported by the target
- Basic Relocation Formula

  S – P + A

  – S: the symbol value
  – P: the place of the use instruction
  – A: addend, adjustment (by the instruction format)

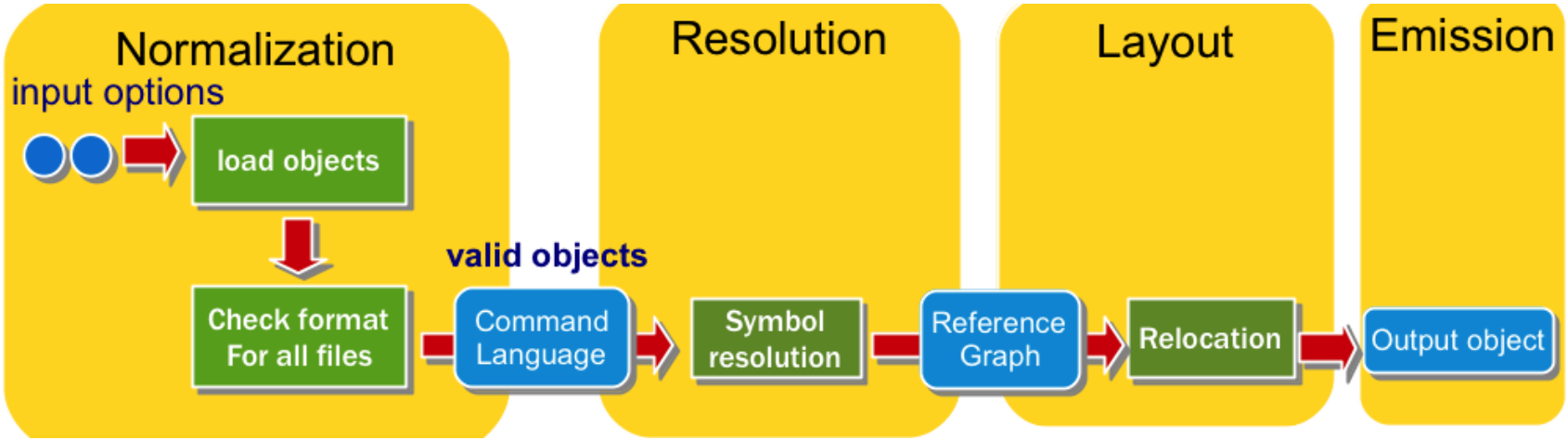


Optimizations on Layout

- Dynamic Prelinking
  - If the system puts shared libraries at a fixed memory location, we can fill GOT with fixed addresses to avoid symbol look up in the loader
- Static Prelinking
  - If the system puts shared libraries at a fixed memory location, we can directly refer to the fixed addresses without any exits
- Symbol Stripping
  - Strip the undefined symbols which is not a exit
- Sections/functions/basic block Reordering
  - Linker knows the address and can perform better reordering

Emission

- Emits the module in the output formats
  - Adds format information
  - Writes down the IR
- In order to improve both cache and page locality, MCLinker collects and performs most file operations in this stage.
  - MCLinker copies the content in the inputs and applies the resolved reference in this stage.



Outline

- **The History**
  - Target Independent Linkers
  - Post Optimizers
  - Instrumentation Tools
- **The Theory**
  - Linking Language
  - Fragment-reference graph
- **The Future**
  - for GPGPU; for virtual machines
  - The bold project

唐文力 Luba Tang

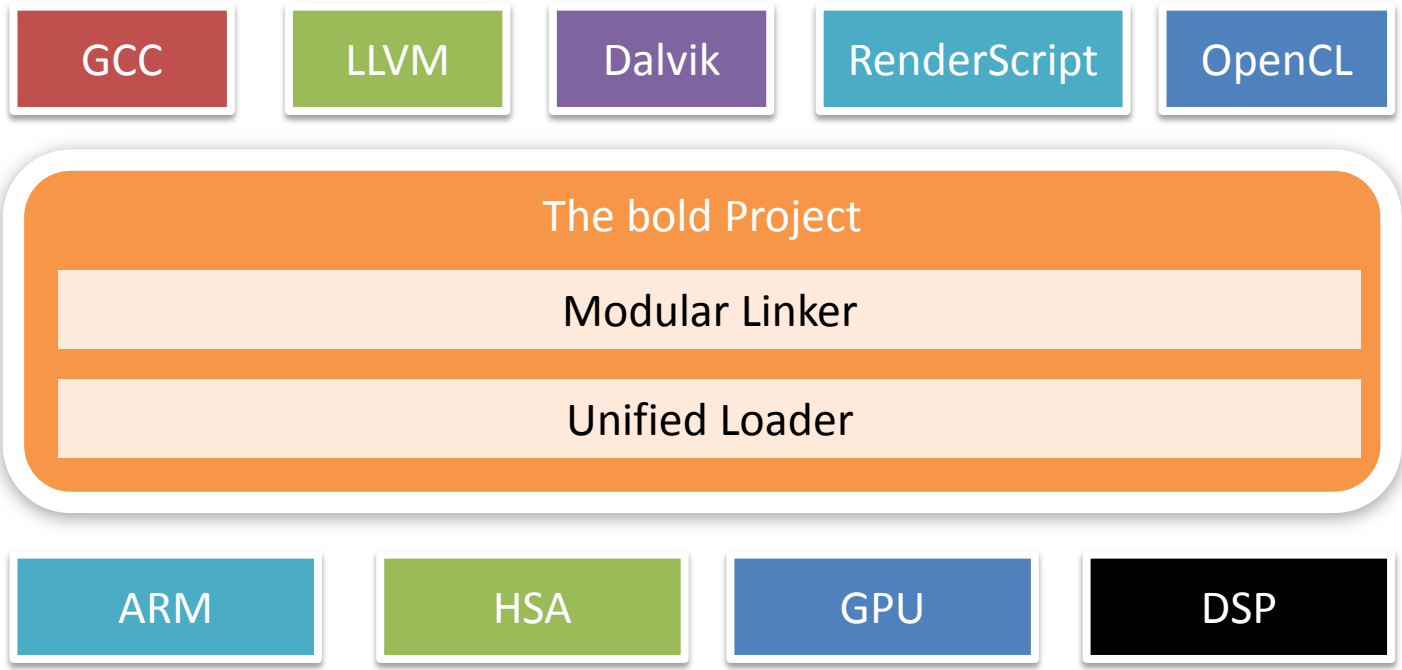
CEO & Founder of Skymizer Inc.

Architect of MCLinker and GYM compiler

Compiler and Linker/Electronic System Level Design

Challenge: Unified Shared Memory of Heterogeneous Many-Core System

- Installation time compilation
  - GPGPU languages (OpenCL, CUDA, RenderScript)
  - Virtual Machine (Dalvik, RenderScript)
- Heterogeneous Many-core System
  - Universal ELF



The bold Project

- **BSD licensing linker**
  - General purpose linker/loader
  - Focus on optimization
  - Linking in parallel

- **OA (Owner agreement) and CA (Committer agreement)**
  - Avoid interest confliction between industry and community.
  - Legal person can not be an owner