Tutorial: Creating an LLVM Toolchain for the Cpu0 Architecture

Release 3.6.0

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CHAPTER

ONE

ABOUT

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- Acknowledgments
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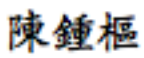
1.1 Authors



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http://jonathan2251.github.io/web/index.html

1.2 Acknowledgments

I would like to thank Sean Silva, chisophugis@gmail.com, for his help, encouragement, and assistance with the Sphinx document generator. Without his help, this book would not have been finished and published online. Also thanking those corrections from readers who make the book more accurate.

1.3 Revision history

Version 3.6.1, Not release yet

Version 3.6.0, Released March 8, 2015 Porting to lld 3.6.

1.4 Licensing

http://llvm.org/docs/DeveloperPolicy.html#license

1.5 Outline of Chapters

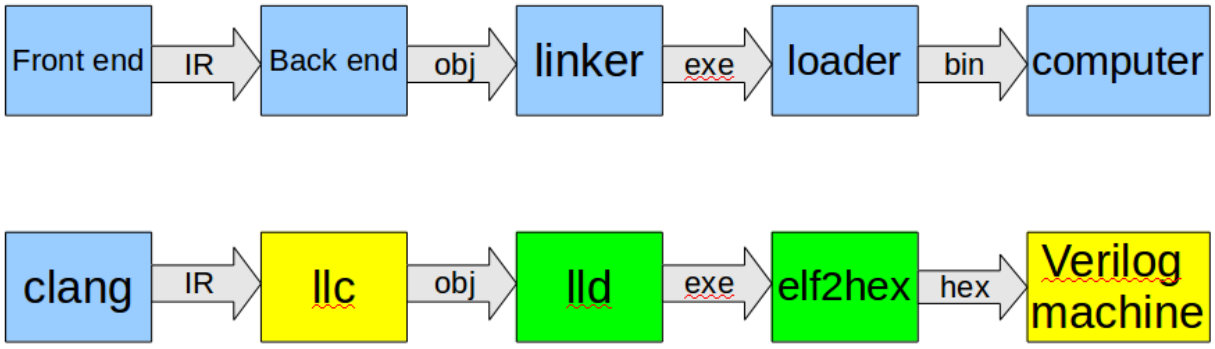

Figure 1.1: Code generation and execution flow

The upper half of Figure 1.1 is the work flow and software package of a computer program be generated and executed. IR stands for Intermediate Representation. The lower half is this book's work flow and software package of the toolchain extended implementation based on llvm. Except clang, the other blocks need to be extended for a new backend development. This book implement the green boxes part. The Cpu0 llvm backend can be find on http://jonathan2251.github.io/lbd/index.html.

This book include:

1. ELF linker for Cpu0 which extended from lld. Chapter 2.
2. The elf2hex extended from llvm-objump. Chapter 2.
3. Optimization. Chapter 3.
4. Porting C standard library from avr libc and software floating point library from LLVM compiler-rt.

With these implementation, reader can generate Cpu0 machine code through Cpu0 llvm backend compiler, linker and elf2hex, then see how it runs on your computer. The pdf and epub are also available in the web.

1.6 Outline of Chapters

Cpu0 ELF linker:

Develop ELF linker for Cpu0 backend based on lld project.

Optimization:

Backend independent optimaization. Under working and I need to avoid something I know since I working with a proprietary company.

Library:

Software floating point library and standard C library supporting. Under working.

CHAPTER

TWO

CPU0 ELF LINKER

- ELF to Hex
- Create Cpu0 backend under LLD
  - Setup Cpu0 backend under lld
  - Cpu0 backend souce code
  - LLD introduction
    - How LLD do the linker job
    - Linking Steps
      - Command line processing
      - Parsing input files
      - Resolving
      - Passes/Optimizations
      - Generate Output File
  - Static linker
    - Run
    - Cpu0 lld structure
  - Dynamic linker
    - Run
    - How to work
- Summary
  - Create a new backend base on LLVM
  - Contribute back to Open Source through working and learning

Like llvm, lld linker include a couple of target in ELF format handling. The term Cpu0 backend used in this chapter can refer to the ELF format handling for Cpu0 target machine under lld, llvm compiler backend, or both. Suppose readers will easy knowing what it refer to.

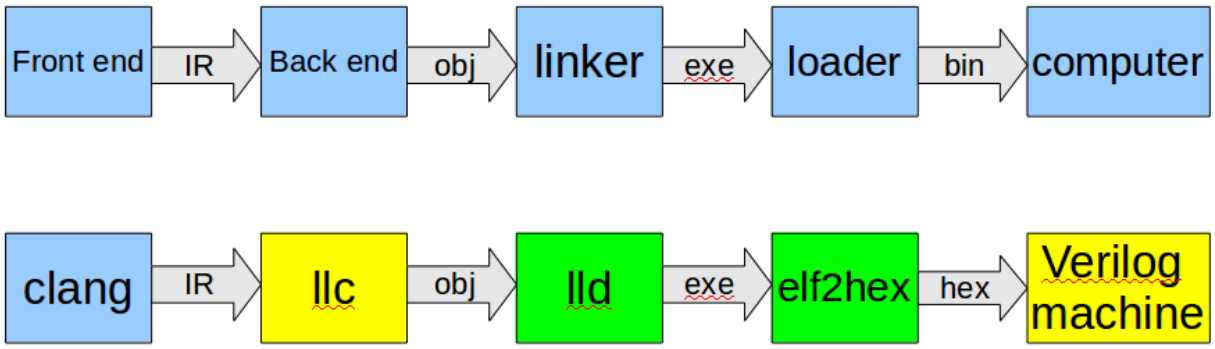

Figure 2.1: Code generation and execution flow

As depicted in Figure 2.1 of chapter About. Beside llvm backend, we implement ELF linker and elf2hex to run on Cpu0 verilog simulator. This chapter extends lld to support Cpu0 backend as well as elf2hex to replace Cpu0 loader. After link with lld, the program with global variables can be allocated in ELF file format layout. Meaning the relocation records of global variables is resolved. In addition, llvm-objdump driver is modified for supporting generate Hex file from ELF by command `llvm-objdump -elf2hex`. With these two tools supported, the global variables exists in section .data and .rodata can be accessed and transfered to Hex file which feeds to Verilog Cpu0 machine and run on your PC/Laptop.

As the previouse chapters mentioned, Cpu0 has two relocation models for static link and dynamic link, respectively, which controlled by option `-relocation-model` in `llc`. This chapter supports the static link fully, and part of dynamic link for demostration purpose. Since dynamic link needs the OS involement and the Cpu0 is run on Verilog bare metal simulator, the dynamic linker program is added and the Cpu0 Verilog code is extended to demostrate these Cpu0 PIC mode instructions are work correctly in dynamice link. However, these part of Cpu0 Verilog codes are not needed in a real machine with OS support, and the Cpu0 lld's and elf2hex's dynamic linker function is not full implemented. They are programmed by a specific shared library name since the shared library locating needs the OS's help (files management is part of OS's job). Without OS, these things cannot be solved and dynamic link is impossible to finish. Anyway, for the dynamic link demostration, we can implement dynamic linker program and adapt lld, elf2hex, and Cpu0 Verilog code to support a specific shared library and verify the dynamic link result. In reality, the Micro CPUs without OS or tiny OS inside only support static link for C language.

About lld please refer LLD web site here [1] and LLD install requirement on Linux here [2]. Currently, lld can be built by: gcc and clang 3.5 compiler on Ubuntu, and gcc on Fedora, as I have tried. On iMac, lld can be built by clang with the Xcode version as the next sub section. If you run with Virtual Machine (VM), please keep your phisical memory size setting over 1GB to avoid insufficient memory link error.

2.1 ELF to Hex

Add elf2hex.h, elf2hex-dlink.h and update llvm-objdump driver to support ELF to Hex for Cpu0 backend as follows,

exlbt/llvm-objdump/elf2hex-dlinker.h

```
#ifdef DLINK

class Cpu0DynFunIndex {
private:
  char soStrtab[20][100];
  int soStrtabSize = 0;

  char exePltName[20][100];
  int exePltNameSize = 0;

  int findPltName(const char* pltName);
public:
  void createPltName(const ObjectFile *o);
  void createStrtab();
  uint16_t correctDynFunIndex(const char* pltName);
};

int Cpu0DynFunIndex::findPltName(const char* pltName) {
  for (int i = 0; i < exePltNameSize; i++)
    if (strcmp(pltName, exePltName[i]) == 0)
```

[1] http://lld.llvm.org/
[2] http://lld.llvm.org/getting_started.html#on-unix-like-systems

```
      return i;
  return -1;
}

void Cpu0DynFunIndex::createPltName(const ObjectFile *Obj) {
  std::error_code ec;
  std::string Error;

  for (const SectionRef &Section : Obj->sections()) {
    if (error(ec)) return;
    StringRef Name;
    StringRef Contents;
    uint64_t BaseAddr;
    bool BSS;
    if (error(Section.getName(Name))) continue;
    if (error(Section.getContents(Contents))) continue;
    BaseAddr = Section.getAddress();
    BSS = Section.isBSS();

    if (Name == ".strtab") {
      int num_dyn_entry = 0;
      FILE *fd_num_dyn_entry;
      fd_num_dyn_entry = fopen("dlconfig/num_dyn_entry", "r");
      if (fd_num_dyn_entry != NULL) {
        fscanf(fd_num_dyn_entry, "%d", &num_dyn_entry);
      }
      fclose(fd_num_dyn_entry);

      for (std::size_t addr = 2+strlen(".PLT0"), end = Contents.size();
           addr < end; ) {
        if (Contents.substr(addr, strlen("__plt_")) != "__plt_")
          break;
        strcpy(exePltName[exePltNameSize], Contents.data()+addr);
        addr = addr + strlen(exePltName[exePltNameSize]) + 1;
        exePltNameSize++;
      }
      break;
    }
  }
}

void Cpu0DynFunIndex::createStrtab() {
  FILE *fd_dynstrAscii;

  fd_dynstrAscii = fopen("dlconfig/dynstrAscii", "r");
  if (fd_dynstrAscii == NULL)
    fclose(fd_dynstrAscii);
  assert(fd_dynstrAscii != NULL && "fd_dynstr == NULL");
  int i = 0;
  // function                 result on EOF or error
  // --------                 ----------------------
  // fgets()                  NULL
  // fscanf()                 number of succesful conversions
  //                            less than expected
  // fgetc()                  EOF
  // fread()                  number of elements read
  //                            less than expected
  int j = 0;
```

```
  for (i=0; 1; i++) {
    j=fscanf(fd_dynstrAscii, "%s", soStrtab[i]);
    if (j != 1)
      break;
  }
  soStrtabSize = i;
  fclose(fd_dynstrAscii);
}

uint16_t Cpu0DynFunIndex::correctDynFunIndex(const char* pltName) {
  int i = findPltName(pltName);
  if (i != -1) {
    int j = 0;
    for (j=0; j < soStrtabSize; j++)
      if (strcmp(soStrtab[j], (const char*)exePltName[i]+strlen("__plt_")) == 0)
        break;
    if (j == soStrtabSize) {
      outs() << "cannot find " << exePltName[i] << "\n";
      exit(1);
    }
    j++;
    return (uint16_t)(j & 0xffff);
  }
  return (uint16_t)0;
}

Cpu0DynFunIndex cpu0DynFunIndex;

static void DisassembleSoInHexFormat(const ObjectFile *Obj
/*, bool InlineRelocs*/  , std::unique_ptr<MCDisassembler>& DisAsm,
  std::unique_ptr<MCInstPrinter>& IP, uint64_t& lastDumpAddr) {
  std::string Error;
  uint64_t soLastPrintAddr = 0;
  FILE *fd_so_func_offset;
  int num_dyn_entry = 0;

  fd_so_func_offset = fopen("dlconfig/so_func_offset", "w");
  if (fd_so_func_offset == NULL)
    fclose(fd_so_func_offset);
  assert(fd_so_func_offset != NULL && "fd_so_func_offset == NULL");

#ifdef ELF2HEX_DEBUG
  errs() << format("!lastDumpAddr %8" PRIx64 "\n", lastDumpAddr);
#endif
  std::error_code ec;
  for (const SectionRef &Section : Obj->sections()) {
    if (error(ec)) break;
    StringRef Name;
    StringRef Contents;
    uint64_t BaseAddr;
    if (error(Section.getName(Name))) continue;
    if (error(Section.getContents(Contents))) continue;
    BaseAddr = Section.getAddress();
  #ifdef ELF2HEX_DEBUG
    errs() << "Name " << Name << format("  BaseAddr %8" PRIx64 "\n", BaseAddr);
    errs() << format("!!lastDumpAddr %8" PRIx64 "\n", lastDumpAddr);
  #endif
    bool text;
```

```
text = Section.isText();
if (!text) {
  continue;
}
// It's .text section
uint64_t SectionAddr;
SectionAddr = Section.getAddress();

// Make a list of all the symbols in this section.
std::vector<std::pair<uint64_t, StringRef> > Symbols;
for (const SymbolRef &Symbol : Obj->symbols()) {
  if (Section.containsSymbol(Symbol)) {
    uint64_t Address;
    if (error(Symbol.getAddress(Address))) break;
    if (Address == UnknownAddressOrSize) continue;
    Address -= SectionAddr;

    StringRef Name;
    if (error(Symbol.getName(Name))) break;
    Symbols.push_back(std::make_pair(Address, Name));
  }
}

// Sort the symbols by address, just in case they didn't come in that way.
array_pod_sort(Symbols.begin(), Symbols.end());

// Make a list of all the relocations for this section.
std::vector<RelocationRef> Rels;

// Sort relocations by address.
std::sort(Rels.begin(), Rels.end(), RelocAddressLess);

StringRef SegmentName = "";
if (const MachOObjectFile *MachO =
    dyn_cast<const MachOObjectFile>(Obj)) {
  DataRefImpl DR = Section.getRawDataRefImpl();
  SegmentName = MachO->getSectionFinalSegmentName(DR);
}
StringRef name;
if (error(Section.getName(name))) break;
if (name == ".plt") continue;
outs() << "/*" << "Disassembly of section ";
if (!SegmentName.empty())
  outs() << SegmentName << ",";
outs() << name << ':' << "*/";

// If the section has no symbols just insert a dummy one and disassemble
// the whole section.
if (Symbols.empty())
  Symbols.push_back(std::make_pair(0, name));

SmallString<40> Comments;
raw_svector_ostream CommentStream(Comments);

StringRef BytesStr;
if (error(Section.getContents(BytesStr))) break;
ArrayRef<uint8_t> Bytes(reinterpret_cast<const uint8_t *>(BytesStr.data()),
                        BytesStr.size());
```

```
uint64_t Size;
uint64_t Index;
uint64_t SectSize;
SectSize = Section.getSize();

std::vector<RelocationRef>::const_iterator rel_cur = Rels.begin();
std::vector<RelocationRef>::const_iterator rel_end = Rels.end();
// Disassemble symbol by symbol.
for (unsigned si = 0, se = Symbols.size(); si != se; ++si) {
  uint64_t Start = Symbols[si].first;
  uint64_t End;
  // The end is either the size of the section or the beginning of the next
  // symbol.
  if (si == se - 1)
    End = SectSize;
  // Make sure this symbol takes up space.
  else if (Symbols[si + 1].first != Start)
    End = Symbols[si + 1].first - 1;
  else {
    // This symbol has the same address as the next symbol. Skip it.
    fprintf(fd_so_func_offset, "%02x ",
            (uint8_t)(Symbols[si].first >> 24));
    fprintf(fd_so_func_offset, "%02x ",
            (uint8_t)((Symbols[si].first >> 16) & 0xFF));
    fprintf(fd_so_func_offset, "%02x ",
            (uint8_t)((Symbols[si].first >> 8) & 0xFF));
    fprintf(fd_so_func_offset, "%02x    ",
            (uint8_t)((Symbols[si].first) & 0xFF));
    std::string str = Symbols[si].second.str();
    std::size_t idx = 0;
    std::size_t strSize = 0;
    for (idx = 0, strSize = str.size(); idx < strSize; idx++) {
      fprintf(fd_so_func_offset, "%c%c ",
              hexdigit((str[idx] >> 4) & 0xF, true),
              hexdigit(str[idx] & 0xF, true));
    }
    for (idx = strSize; idx < 48; idx++) {
      fprintf(fd_so_func_offset, "%02x ", 0);
    }
    fprintf(fd_so_func_offset, "/* %s */\n", Symbols[si].second.begin());
    num_dyn_entry++;

    outs() << '\n' << "/*" << Symbols[si].second << ":*/\n";
    continue;
  }

  soLastPrintAddr = Symbols[si].first;
  fprintf(fd_so_func_offset, "%02x ", (uint8_t)(Symbols[si].first >> 24));
  fprintf(fd_so_func_offset, "%02x ",
          (uint8_t)((Symbols[si].first >> 16) & 0xFF));
  fprintf(fd_so_func_offset, "%02x ",
          (uint8_t)((Symbols[si].first >> 8) & 0xFF));
  fprintf(fd_so_func_offset, "%02x    ",
          (uint8_t)((Symbols[si].first) & 0xFF));
  std::string str = Symbols[si].second.str();
  std::size_t idx = 0;
  std::size_t strSize = 0;
  for (idx = 0, strSize = str.size(); idx < strSize; idx++) {
```

```
        fprintf(fd_so_func_offset, "%c%c ",
                hexdigit((str[idx] >> 4) & 0xF, true),
                hexdigit(str[idx] & 0xF, true));
      }
      for (idx = strSize; idx < 48; idx++) {
        fprintf(fd_so_func_offset, "%02x ", 0);
      }
      fprintf(fd_so_func_offset, "/* %s */\n", Symbols[si].second.begin());
      num_dyn_entry++;

      outs() << '\n' << "/*" << Symbols[si].second << ":*/\n";
#ifndef NDEBUG
        raw_ostream &DebugOut = DebugFlag ? dbgs() : nulls();
#else
        raw_ostream &DebugOut = nulls();
#endif

      for (Index = Start; Index < End; Index += Size) {
        MCInst Inst;
        if (DisAsm->getInstruction(Inst, Size, Bytes.slice(Index),
                                   SectionAddr + Index, DebugOut,
                                   CommentStream)) {
          outs() << format("/*%8" PRIx64 ":*/", lastDumpAddr + Index);
          if (!NoShowRawInsn) {
            outs() << "\t";
            DumpBytes(StringRef(
                reinterpret_cast<const char *>(Bytes.data()) + Index, Size));
          }
          outs() << "/*";
          IP->printInst(&Inst, outs(), "");
          outs() << CommentStream.str();
          outs() << "*/";
          Comments.clear();
          outs() << "\n";
        } else {
          errs() << ToolName << ": warning: invalid instruction encoding\n";
          if (Size == 0)
            Size = 1; // skip illegible bytes
        }

        //  outs() << "Size = " << Size <<  "Index = " << Index << "lastDumpAddr = "
        //         << lastDumpAddr << "\n"; // debug
        // Print relocation for instruction.
        while (rel_cur != rel_end) {
          bool hidden = false;
          uint64_t addr;
          SmallString<16> name;
          SmallString<32> val;

          // If this relocation is hidden, skip it.
          if (error(rel_cur->getHidden(hidden))) goto skip_print_rel;
          if (hidden) goto skip_print_rel;

          if (error(rel_cur->getOffset(addr))) goto skip_print_rel;
          // Stop when rel_cur's address is past the current instruction.
          if (addr >= Index + Size) break;
          if (error(rel_cur->getTypeName(name))) goto skip_print_rel;
          if (error(rel_cur->getValueString(val))) goto skip_print_rel;
```

```
          outs() << format("\t\t\t/*%8" PRIx64 ": ", SectionAddr + addr) << name
                 << "\t" << val << "*/\n";

        skip_print_rel:
          ++rel_cur;
        }
        lastDumpAddr += Index;
      }
      soLastPrintAddr = End;
    #ifdef ELF2HEX_DEBUG
      errs() << format("SectionAddr + Index = %8" PRIx64 "\n", SectionAddr + Index);
      errs() << format("lastDumpAddr %8" PRIx64 "\n", lastDumpAddr);
    #endif
    }
  }
// Dump share obj or lib
// Fix the issue that __tls_get_addr appear as file offset 0.
// Old lld version the __tls_get_addr appear at the last function name.
  std::pair<uint64_t, StringRef> dummy(soLastPrintAddr, "dummy");
  fprintf(fd_so_func_offset, "%02x ", (uint8_t)(dummy.first >> 24));
  fprintf(fd_so_func_offset, "%02x ", (uint8_t)((dummy.first >> 16) & 0xFF));
  fprintf(fd_so_func_offset, "%02x ", (uint8_t)((dummy.first >> 8) & 0xFF));
  fprintf(fd_so_func_offset, "%02x    ", (uint8_t)((dummy.first) & 0xFF));
  std::string str = dummy.second.str();
  std::size_t idx = 0;
  std::size_t strSize = 0;
  for (idx = 0, strSize = str.size(); idx < strSize; idx++) {
    fprintf(fd_so_func_offset, "%c%c ", hexdigit((str[idx] >> 4) & 0xF, true)
            , hexdigit(str[idx] & 0xF, true));
  }
  for (idx = strSize; idx < 48; idx++) {
    fprintf(fd_so_func_offset, "%02x ", 0);
  }
  fprintf(fd_so_func_offset, "/* %s */\n", dummy.second.begin());
  num_dyn_entry++;
  outs() << '\n' << "/*" << dummy.second << ":*/\n";
  FILE *fd_num_dyn_entry;
  fd_num_dyn_entry = fopen("dlconfig/num_dyn_entry", "w");
  if (fd_num_dyn_entry != NULL) {
    fprintf(fd_num_dyn_entry, "%d\n", num_dyn_entry);
  }
  fclose(fd_num_dyn_entry);
}

static void PrintSoDataSections(const ObjectFile *o, uint64_t& lastDumpAddr,
                                bool isLittleEndian) {
  std::error_code ec;

  for (const SectionRef &Section : o->sections()) {
    if (error(ec)) return;
    StringRef Name;
    StringRef Contents;
    uint64_t BaseAddr;
    bool BSS;
    if (error(Section.getName(Name))) continue;
    if (error(Section.getContents(Contents))) continue;
    BaseAddr = Section.getAddress();
    BSS = Section.isBSS();
```

```
    if (Name == ".dynsym") {
      int num_dyn_entry = 0;
      FILE *fd_num_dyn_entry;
      fd_num_dyn_entry = fopen("dlconfig/num_dyn_entry", "r");
      if (fd_num_dyn_entry != NULL) {
        fscanf(fd_num_dyn_entry, "%d", &num_dyn_entry);
      }
      fclose(fd_num_dyn_entry);
      raw_fd_ostream fd_dynsym("dlconfig/dynsym", ec, sys::fs::F_Text);
      int count = 0;
      for (std::size_t addr = 0, end = Contents.size(); addr < end; addr += 16) {
        if (isLittleEndian) {
          fd_dynsym << hexdigit((Contents[addr+3] >> 4) & 0xF, true)
                    << hexdigit(Contents[addr+3] & 0xF, true) << " ";
          fd_dynsym << hexdigit((Contents[addr+2] >> 4) & 0xF, true)
                    << hexdigit(Contents[addr+2] & 0xF, true) << " ";
          fd_dynsym << hexdigit((Contents[addr+1] >> 4) & 0xF, true)
                    << hexdigit(Contents[addr+1] & 0xF, true) << " ";
          fd_dynsym << hexdigit((Contents[addr] >> 4) & 0xF, true)
                    << hexdigit(Contents[addr] & 0xF, true) << " ";
        }
        else {
          fd_dynsym << hexdigit((Contents[addr] >> 4) & 0xF, true)
                    << hexdigit(Contents[addr] & 0xF, true) << " ";
          fd_dynsym << hexdigit((Contents[addr+1] >> 4) & 0xF, true)
                    << hexdigit(Contents[addr+1] & 0xF, true) << " ";
          fd_dynsym << hexdigit((Contents[addr+2] >> 4) & 0xF, true)
                    << hexdigit(Contents[addr+2] & 0xF, true) << " ";
          fd_dynsym << hexdigit((Contents[addr+3] >> 4) & 0xF, true)
                    << hexdigit(Contents[addr+3] & 0xF, true) << " ";
        }
        count++;
      }
      for (int i = count; i < num_dyn_entry; i++) {
        fd_dynsym << "00 00 00 00 ";
      }
    }
    else if (Name == ".dynstr") {
      raw_fd_ostream fd_dynstr("dlconfig/dynstr", ec, sys::fs::F_Text);
      raw_fd_ostream fd_dynstrAscii("dlconfig/dynstrAscii", ec,
                                    sys::fs::F_Text);
      for (std::size_t addr = 0, end = Contents.size(); addr < end; addr++) {
        fd_dynstr << hexdigit((Contents[addr] >> 4) & 0xF, true)
                  << hexdigit(Contents[addr] & 0xF, true) << " ";
        if (addr == 0)
          continue;
        if (Contents[addr] == '\0')
          fd_dynstrAscii << "\n";
        else
          fd_dynstrAscii << Contents[addr];
      }
    }
  }
}

#endif // DLINK
```

exlbt/llvm-objdump/elf2hex.h

```
//===-------------------------------- elf2hex.cpp -------------------------------===//
//
//                     The LLVM Compiler Infrastructure
//
// This file is distributed under the University of Illinois Open Source
// License. See LICENSE.TXT for details.
//
//===----------------------------------------------------------------------------===//
//
// This program is a utility that works with llvm-objdump.
//
//===----------------------------------------------------------------------------===//

#include <stdio.h>
#include "llvm/Support/raw_ostream.h"
#define DLINK
//#define ELF2HEX_DEBUG

static cl::opt<bool>
ConvertElf2Hex("elf2hex",
cl::desc("Display the hex content of verilog cpu0 needed sections"));

static cl::opt<bool>
LittleEndian("le",
cl::desc("Little endian format"));

#ifdef DLINK
  static cl::opt<bool>
  DumpSo("cpu0dumpso",
  cl::desc("Dump shared library .so"));

  static cl::opt<bool>
  LinkSo("cpu0linkso",
  cl::desc("Link shared library .so"));

  #include "elf2hex-dlinker.h"
#endif

// Modified from PrintSectionHeaders()
static uint64_t GetSectionHeaderStartAddress(const ObjectFile *Obj,
  StringRef sectionName) {
//  outs() << "Sections:\n"
//            "Idx Name          Size      Address          Type\n";
  std::error_code ec;
  unsigned i = 0;
  for (const SectionRef &Section : Obj->sections()) {
    if (error(ec)) return 0;
    StringRef Name;
    if (error(Section.getName(Name))) return 0;
    uint64_t Address;
    Address = Section.getAddress();
    uint64_t Size;
    Size = Section.getSize();
    bool Text;
    Text = Section.isText();
    if (Name == sectionName)
```

```
      return Address;
    else
      return 0;
    ++i;
  }
  return 0;
}

// Fill /*address*/ 00 00 00 00 [startAddr..endAddr] from startAddr to endAddr.
// Include startAddr and endAddr.
static void Fill0s(uint64_t startAddr, uint64_t endAddr) {
  std::size_t addr;

  assert((startAddr <= endAddr) && "startAddr must <= BaseAddr");
  // Fill /*address*/ bytes is odd for 4 by 00
  outs() << format("/*%8" PRIx64 " */", startAddr);
  // Fill /*address*/ 00 00 00 00 for 4 bytes alignment (1 Cpu0 word size)
  for (addr = startAddr; addr < endAddr; addr += 4) {
    outs() << format("/*%8" PRIx64 " */", addr);
    outs() << format("%02" PRIx64 " ", 0) << format("%02" PRIx64 " ", 0) \
    << format("%02" PRIx64 " ", 0) << format("%02" PRIx64 " ", 0) << '\n';
  }

  return;
}

static void PrintDataSection(const ObjectFile *o, uint64_t& lastDumpAddr,
  SectionRef Section) {
  std::string Error;
  StringRef Name;
  StringRef Contents;
  uint64_t BaseAddr;
  bool BSS;
  uint64_t size;
  if (error(Section.getName(Name))) return;
  if (error(Section.getContents(Contents))) return;
  BaseAddr = Section.getAddress();
  BSS = Section.isBSS();

  size = (Contents.size()+3)/4*4;
  if (Contents.size() <= 0) {
    return;
  }

  outs() << "/*Contents of section " << Name << ":*/\n";
  // Dump out the content as hex and printable ascii characters.
  for (std::size_t addr = 0, end = Contents.size(); addr < end; addr += 16) {
    outs() << format("/*%8" PRIx64 " */", BaseAddr + addr);
    // Dump line of hex.
    for (std::size_t i = 0; i < 16; ++i) {
      if (i != 0 && i % 4 == 0)
        outs() << ' ';
      if (addr + i < end)
        outs() << hexdigit((Contents[addr + i] >> 4) & 0xF, true)
               << hexdigit(Contents[addr + i] & 0xF, true) << " ";
    }
    // Print ascii.
    outs() << "/*" << "  ";
```

```
    for (std::size_t i = 0; i < 16 && addr + i < end; ++i) {
      if (std::isprint(static_cast<unsigned char>(Contents[addr + i]) & 0xFF))
        outs() << Contents[addr + i];
      else
        outs() << ".";
    }
    outs() << "*/" << "\n";
  }
  for (std::size_t i = Contents.size(); i < size; i++) {
    outs() << "00 ";
  }
  outs() << "\n";
#ifdef ELF2HEX_DEBUG
  errs() << "Name " << Name << "  BaseAddr ";
  errs() << format("%8" PRIx64 " Contents.size() ", BaseAddr);
  errs() << format("%8" PRIx64 " size ", Contents.size());
  errs() << format("%8" PRIx64 " \n", size);
#endif
  // save the end address of this section to lastDumpAddr
  lastDumpAddr = BaseAddr + size;
}

// Modified from DisassembleObject()
static void DisassembleObjectInHexFormat(const ObjectFile *Obj
/*, bool InlineRelocs*/  , std::unique_ptr<MCDisassembler>& DisAsm,
  std::unique_ptr<MCInstPrinter>& IP, uint64_t& lastDumpAddr) {

#ifdef ELF2HEX_DEBUG
  errs() << format("!lastDumpAddr %8" PRIx64 "\n", lastDumpAddr);
#endif
  std::error_code ec;
  for (const SectionRef &Section : Obj->sections()) {
    if (error(ec)) break;
    StringRef Name;
    StringRef Contents;
    uint64_t BaseAddr;
    if (error(Section.getName(Name))) continue;
    if (error(Section.getContents(Contents))) continue;
    BaseAddr = Section.getAddress();
    if (BaseAddr < 0x100)
      continue;
  #ifdef ELF2HEX_DEBUG
    errs() << "Name " << Name << format("  BaseAddr %8" PRIx64 "\n", BaseAddr);
    errs() << format("!!lastDumpAddr %8" PRIx64 "\n", lastDumpAddr);
  #endif
    bool text;
    text = Section.isText();
    if (!text) {
    #ifdef ELF2HEX_DEBUG
      errs() << "!text\n";
    #endif
      if (lastDumpAddr < BaseAddr) {
        Fill0s(lastDumpAddr, BaseAddr - 1);
        lastDumpAddr = BaseAddr;
      }
      if (Name == ".got.plt") {
        uint64_t BaseAddr;
        BaseAddr = Section.getAddress();
```

```
    #ifdef DLINK
      if (LinkSo) {
        raw_fd_ostream fd_global_offset("dlconfig/global_offset", ec,
                                        sys::fs::F_Text);
        fd_global_offset << format("%02" PRIx64 " ", BaseAddr >> 24);
        fd_global_offset << format("%02" PRIx64 " ", (BaseAddr >> 16) & 0xFF);
        fd_global_offset << format("%02" PRIx64 " ", (BaseAddr >> 8) & 0xFF);
        fd_global_offset << format("%02" PRIx64 "    ", BaseAddr & 0xFF);
      }
    #endif
      PrintDataSection(Obj, lastDumpAddr, Section);
    }
    else if ((Name == ".bss" || Name == ".sbss") && Contents.size() > 0) {
      uint64_t size = (Contents.size() + 3)/4*4;
      Fill0s(BaseAddr, BaseAddr + size - 1);
      lastDumpAddr = BaseAddr + size;
      continue;
    }
    else {
      PrintDataSection(Obj, lastDumpAddr, Section);
    }
    continue;
  }
  else {
    if (lastDumpAddr < BaseAddr) {
      Fill0s(lastDumpAddr, BaseAddr - 1);
      lastDumpAddr = BaseAddr;
    }
  }
  // It's .text section
  uint64_t SectionAddr;
  SectionAddr = Section.getAddress();
  uint64_t SectSize = Section.getSize();
  if (!SectSize)
    continue;

  // Make a list of all the symbols in this section.
  std::vector<std::pair<uint64_t, StringRef> > Symbols;
  for (const SymbolRef &Symbol : Obj->symbols()) {
    if (Section.containsSymbol(Symbol)) {
      uint64_t Address;
      if (error(Symbol.getAddress(Address)))
        break;
      if (Address == UnknownAddressOrSize)
        continue;
      Address -= SectionAddr;
      if (Address >= SectSize)
        continue;

      StringRef Name;
      if (error(Symbol.getName(Name))) break;
      Symbols.push_back(std::make_pair(Address, Name));
    }
  }

  // Sort the symbols by address, just in case they didn't come in that way.
  array_pod_sort(Symbols.begin(), Symbols.end());
#ifdef ELF2HEX_DEBUG
```

```
    for (unsigned si = 0, se = Symbols.size(); si != se; ++si) {
        errs() << '\n' << "/*" << Symbols[si].first << "  " << Symbols[si].second << ":*/\n";
    }
  #endif

    // Make a list of all the relocations for this section.
    std::vector<RelocationRef> Rels;

    // Sort relocations by address.
    std::sort(Rels.begin(), Rels.end(), RelocAddressLess);

    StringRef SegmentName = "";
    if (const MachOObjectFile *MachO =
        dyn_cast<const MachOObjectFile>(Obj)) {
      DataRefImpl DR = Section.getRawDataRefImpl();
      SegmentName = MachO->getSectionFinalSegmentName(DR);
    }
    StringRef name;
    if (error(Section.getName(name))) break;
    outs() << "/*" << "Disassembly of section ";
    if (!SegmentName.empty())
      outs() << SegmentName << ",";
    outs() << name << ':' << "*/";

    // If the section has no symbols just insert a dummy one and disassemble
    // the whole section.
    if (Symbols.empty())
      Symbols.push_back(std::make_pair(0, name));

    SmallString<40> Comments;
    raw_svector_ostream CommentStream(Comments);

    StringRef BytesStr;
    if (error(Section.getContents(BytesStr))) break;
    ArrayRef<uint8_t> Bytes(reinterpret_cast<const uint8_t *>(BytesStr.data()),
                            BytesStr.size());
    uint64_t Size;
    uint64_t Index;
    SectSize = Section.getSize();

    std::vector<RelocationRef>::const_iterator rel_cur = Rels.begin();
    std::vector<RelocationRef>::const_iterator rel_end = Rels.end();
    // Disassemble symbol by symbol.
    for (unsigned si = 0, se = Symbols.size(); si != se; ++si) {
      uint64_t Start = Symbols[si].first;
      uint64_t End;
      // The end is either the size of the section or the beginning of the next
      // symbol.
      if (si == se - 1)
        End = SectSize;
      // Make sure this symbol takes up space.
      else if (Symbols[si + 1].first != Start)
        End = Symbols[si + 1].first - 1;
      else {
        outs() << '\n' << "/*" << Symbols[si].second << ":*/\n";
        continue;
      }
```

```
      outs() << '\n' << "/*" << Symbols[si].second << ":*/\n";
    #ifdef DLINK
      uint16_t funIndex = 0;
      if (LinkSo) {
      // correctDynFunIndex
        funIndex = cpu0DynFunIndex.correctDynFunIndex(Symbols[si].second.data());
      }
    #endif

#ifndef NDEBUG
        raw_ostream &DebugOut = DebugFlag ? dbgs() : nulls();
#else
        raw_ostream &DebugOut = nulls();
#endif

      for (Index = Start; Index < End; Index += Size) {
        MCInst Inst;

    #ifdef DLINK
  #ifdef ELF2HEX_DEBUG
    errs() << "funIndex: " << funIndex << "Index: " << Index << "Size: " << Size << "\n";
  #endif
        if (LinkSo && funIndex && Index == Start) {
          outs() << format("/*%8" PRIx64 ":*/\t", SectionAddr + Index);
          outs() << "01 6b " << format("%02" PRIx64, (funIndex*4+16) & 0xff00)
                  << format(" %02" PRIx64, (funIndex*4+16) & 0x00ff);
          outs() << "                                  /* ld\t$t9, "
                 << funIndex*4+16 << "($gp)\n";
        }
        else
    #endif
        {
          if (DisAsm->getInstruction(Inst, Size, Bytes.slice(Index),
                                     SectionAddr + Index, DebugOut,
                                     CommentStream)) {
            outs() << format("/*%8" PRIx64 ":*/", SectionAddr + Index);
            if (!NoShowRawInsn) {
              outs() << "\t";
              DumpBytes(StringRef(
                  reinterpret_cast<const char *>(Bytes.data()) + Index, Size));
            }
            outs() << "/*";
            IP->printInst(&Inst, outs(), "");
            outs() << CommentStream.str();
            outs() << "*/";
            Comments.clear();
            outs() << "\n";
          } else {
            errs() << ToolName << ": warning: invalid instruction encoding\n";
            if (Size == 0)
              Size = 1; // skip illegible bytes
          }
        }

        //  outs() << "Size = " << Size <<  "Index = " << Index << "lastDumpAddr = "
        //         << lastDumpAddr << "\n"; // debug
        // Print relocation for instruction.
        while (rel_cur != rel_end) {
```

```
          bool hidden = false;
          uint64_t addr;
          SmallString<16> name;
          SmallString<32> val;

          // If this relocation is hidden, skip it.
          if (error(rel_cur->getHidden(hidden))) goto skip_print_rel;
          if (hidden) goto skip_print_rel;

          if (error(rel_cur->getOffset(addr))) goto skip_print_rel;
          // Stop when rel_cur's address is past the current instruction.
          if (addr >= Index + Size) break;
          if (error(rel_cur->getTypeName(name))) goto skip_print_rel;
          if (error(rel_cur->getValueString(val))) goto skip_print_rel;

          outs() << format("\t\t\t/*%8" PRIx64 ": ", SectionAddr + addr) << name
                 << "\t" << val << "*/\n";

        skip_print_rel:
          ++rel_cur;
        }
      }
    #ifdef ELF2HEX_DEBUG
      errs() << format("SectionAddr + Index = %8" PRIx64 "\n", SectionAddr + Index);
      errs() << format("lastDumpAddr %8" PRIx64 "\n", lastDumpAddr);
    #endif
    }
    // In section .plt or .text, the Contents.size() maybe < (SectionAddr + Index)
    if (Contents.size() < (SectionAddr + Index))
      lastDumpAddr = SectionAddr + Index;
    else
      lastDumpAddr = SectionAddr + Contents.size();
  }
}

static uint64_t SectionOffset(const ObjectFile *o, StringRef secName) {
  std::error_code ec;

  for (const SectionRef &Section : o->sections()) {
    if (error(ec)) return 0;
    StringRef Name;
    StringRef Contents;
    uint64_t BaseAddr;
    bool BSS;
    if (error(Section.getName(Name))) return 0;
    if (error(Section.getContents(Contents))) return 0;
    BaseAddr = Section.getAddress();
    BSS = Section.isBSS();

    if (Name == secName)
      return BaseAddr;
  }
  return 0;
}

static void PrintBootSection(uint64_t pltOffset, bool isLittleEndian) {
  uint64_t offset = pltOffset - 4;
  if (isLittleEndian) {
```

```
    outs() << "/*       0:*/        ";
    outs() << format("%02" PRIx64 " ", (offset & 0xff));
    outs() << format("%02" PRIx64 "", (offset & 0xff00) >> 8);
    outs() << " 00 36";
    outs() << "                                  /*        jmp        0x";
    outs() << format("%02" PRIx64 "%02" PRIx64 " */\n", (offset & 0xff00) >> 8,
                     (offset & 0xff));
    outs() <<
      "/*       4:*/        04 00 00 36                                  /*        jmp        4 */\n"
    outs() << "/*       8:*/        ";
    outs() << format("%02" PRIx64 " ", (offset & 0xff));
    outs() << format("%02" PRIx64 "", (offset & 0xff00) >> 8);
    outs() << " 00 36";
    outs() << "                                  /*        jmp        0x";
    outs() << format("%02" PRIx64 "%02" PRIx64 " */\n", (offset & 0xff00) >> 8,
                     (offset & 0xff));
    outs() <<
      "/*       c:*/        fc ff ff 36                                  /*        jmp        -4 */\n
  }
  else {
    outs() << "/*       0:*/        36 00 ";
    outs() << format("%02" PRIx64 " ", (offset & 0xff00) >> 8);
    outs() << format("%02" PRIx64 "", (offset & 0xff));
    outs() << "                                  /*        jmp        0x";
    outs() << format("%02" PRIx64 "%02" PRIx64 " */\n", (offset & 0xff00) >> 8,
                     (offset & 0xff));
    outs() <<
      "/*       4:*/        36 00 00 04                                  /*        jmp        4 */\n"
    outs() << "/*       8:*/        36 00 ";
    outs() << format("%02" PRIx64 " ", (offset & 0xff00) >> 8);
    outs() << format("%02" PRIx64 "", (offset & 0xff));
    outs() << "                                  /*        jmp        0x";
    outs() << format("%02" PRIx64 "%02" PRIx64 " */\n", (offset & 0xff00) >> 8,
                     (offset & 0xff));
    outs() <<
      "/*       c:*/        36 ff ff fc                                  /*        jmp        -4 */\n
  }
}

#if 0
// Create by ref PrintSymbolTable()
static void FillJTI(const ObjectFile *o) {
  for (const SymbolRef &Symbol : o->symbols()) {
    StringRef JTIBlockName;
    uint64_t BBAddr[0x10000];
    StringRef Name;
    uint64_t Address;
    SymbolRef::Type Type;
    uint64_t Size;
    uint32_t Flags = Symbol.getFlags();
    section_iterator Section = o->section_end();
    if (error(Section->getName(SectionName)))
      SectionName = "";
    if (SectionName != ".rodata") continue;
    if (error(Symbol.getName(Name)))
      continue;
  // For example: Name=JTI8_0 => JTIBlockName=BB8 (rule hit until _)
    if (strncmp(Name.c_str(), "JTI", strlen("JTI") == 0) {
```

```
      int i = 0;
      for (i = strlen("JTI"); Name[i] != '_'; i++);
      if (i > strlen("JTI"))
        JTIBlockName = "BB" + Name.substr(strlen("JTI"), i-strlen("JTI"));
    }
  // Then get all BB8_* address.
    Address = Section.getAddress();
    if (error(Symbol.getSection(Section)))
      continue;
    if (Section != ".text")
      continue;
}
#endif

static void Elf2Hex(const ObjectFile *o) {
  uint64_t lastDumpAddr = 0;

  const Target *TheTarget = getTarget(o);
  // getTarget() will have already issued a diagnostic if necessary, so
  // just bail here if it failed.
  if (!TheTarget)
    return;

  // Package up features to be passed to target/subtarget
  std::string FeaturesStr;
  if (MAttrs.size()) {
    SubtargetFeatures Features;
    for (unsigned i = 0; i != MAttrs.size(); ++i)
      Features.AddFeature(MAttrs[i]);
    FeaturesStr = Features.getString();
  }

  std::unique_ptr<const MCRegisterInfo> MRI(TheTarget->createMCRegInfo(TripleName));
  if (!MRI) {
    errs() << "error: no register info for target " << TripleName << "\n";
    return;
  }

  // Set up disassembler.
  std::unique_ptr<const MCAsmInfo> AsmInfo(
    TheTarget->createMCAsmInfo(*MRI, TripleName));
  if (!AsmInfo) {
    errs() << "error: no assembly info for target " << TripleName << "\n";
    return;
  }

  std::unique_ptr<const MCSubtargetInfo> STI(
    TheTarget->createMCSubtargetInfo(TripleName, "", FeaturesStr));
  if (!STI) {
    errs() << "error: no subtarget info for target " << TripleName << "\n";
    return;
  }

  std::unique_ptr<const MCInstrInfo> MII(TheTarget->createMCInstrInfo());
  if (!MII) {
    errs() << "error: no instruction info for target " << TripleName << "\n";
    return;
  }
```

```
  std::unique_ptr<const MCObjectFileInfo> MOFI(new MCObjectFileInfo);
  MCContext Ctx(AsmInfo.get(), MRI.get(), MOFI.get());

  std::unique_ptr<MCDisassembler> DisAsm(
    TheTarget->createMCDisassembler(*STI, Ctx));
  if (!DisAsm) {
    errs() << "error: no disassembler for target " << TripleName << "\n";
    return;
  }

  std::unique_ptr<const MCInstrAnalysis> MIA(
      TheTarget->createMCInstrAnalysis(MII.get()));

  int AsmPrinterVariant = AsmInfo->getAssemblerDialect();
  std::unique_ptr<MCInstPrinter> IP(TheTarget->createMCInstPrinter(
      AsmPrinterVariant, *AsmInfo, *MII, *MRI, *STI));
  if (!IP) {
    errs() << "error: no instruction printer for target " << TripleName
      << '\n';
    return;
  }

  uint64_t startAddr = GetSectionHeaderStartAddress(o, "_start");
//  outs() << format("_start address:%08" PRIx64 "\n", startAddr);
#ifdef DLINK
  if (DumpSo) {
    DisassembleSoInHexFormat(o, DisAsm, IP, lastDumpAddr);
    PrintSoDataSections(o, lastDumpAddr, LittleEndian);
  }
  else
#endif
  {
    std::error_code EC;
    uint64_t pltOffset = SectionOffset(o, ".plt");
    PrintBootSection(pltOffset, LittleEndian);
  #ifdef DLINK
    if (LinkSo) {
      cpu0DynFunIndex.createPltName(o);
      cpu0DynFunIndex.createStrtab();
      raw_fd_ostream fd_plt_offset("dlconfig/plt_offset", EC,
                                   sys::fs::F_Text);
      fd_plt_offset << format("%08" PRIx64 " ", pltOffset);
    }
  #endif
    lastDumpAddr = 16;
    Fill0s(lastDumpAddr, 0x100);
    lastDumpAddr = 0x100;
    DisassembleObjectInHexFormat(o, DisAsm, IP, lastDumpAddr);
  }
}
```

exlbt/llvm-objdump/llvm-objdump.cpp

```
#include "elf2hex.h"

static void DumpObject(const ObjectFile *o) {
```

```
  outs() << '\n';
  if (ConvertElf2Hex)
    outs() << "/*";
  outs() << o->getFileName()
         << ":\tfile format " << o->getFileFormatName() << "\n\n";
  if (ConvertElf2Hex)
    outs() << "*/";
  outs() << "\n\n";

  if (Disassemble)
    DisassembleObject(o, Relocations);
  if (Relocations && !Disassemble)
    PrintRelocations(o);
  if (SectionHeaders)
    PrintSectionHeaders(o);
  if (SectionContents)
    PrintSectionContents(o);
  if (ConvertElf2Hex)
    Elf2Hex(o);
  if (SymbolTable)
    PrintSymbolTable(o);
  if (UnwindInfo)
    PrintUnwindInfo(o);
  if (PrivateHeaders)
    printPrivateFileHeader(o);
  if (ExportsTrie)
    printExportsTrie(o);
  if (Rebase)
    printRebaseTable(o);
  if (Bind)
    printBindTable(o);
  if (LazyBind)
    printLazyBindTable(o);
  if (WeakBind)
    printWeakBindTable(o);
}

int main(int argc, char **argv) {
  // Print a stack trace if we signal out.
  sys::PrintStackTraceOnErrorSignal();
  PrettyStackTraceProgram X(argc, argv);
  llvm_shutdown_obj Y;  // Call llvm_shutdown() on exit.

  // Initialize targets and assembly printers/parsers.
  llvm::InitializeAllTargetInfos();
  llvm::InitializeAllTargetMCs();
  llvm::InitializeAllAsmParsers();
  llvm::InitializeAllDisassemblers();

  // Register the target printer for --version.
  cl::AddExtraVersionPrinter(TargetRegistry::printRegisteredTargetsForVersion);

  cl::ParseCommandLineOptions(argc, argv, "llvm object file dumper\n");
  TripleName = Triple::normalize(TripleName);

  ToolName = argv[0];

  // Defaults to a.out if no filenames specified.
```

```
  if (InputFilenames.size() == 0)
    InputFilenames.push_back("a.out");

  if (!Disassemble
      && !Relocations
      && !SectionHeaders
      && !SectionContents
      && !ConvertElf2Hex
      && !SymbolTable
      && !UnwindInfo
      && !PrivateHeaders
      && !ExportsTrie
      && !Rebase
      && !Bind
      && !LazyBind
      && !WeakBind
      && !(UniversalHeaders && MachOOpt)) {
    cl::PrintHelpMessage();
    return 2;
  }

  std::for_each(InputFilenames.begin(), InputFilenames.end(),
                DumpInput);

  return ReturnValue;
}
```

The code included in "#ifdef DLINK" are for dynamic linker support. The elf2hex.h supports both endian dump.

2.2 Create Cpu0 backend under LLD

2.2.1 Setup Cpu0 backend under lld

LLD project is underdevelopment and can be compiled only with c++11 standard (C++2011 year announced standard). For iMac, our software is OS X version 10.9.1 and Xcode version 5.0.2. For old iMac software version, you can install VM (such as Virtual Box) and build lld as Linux platform. Please download lld from llvm web [3] and put lld souce code on {llvm-src}/tools/lld just like we download llvm and clang as shown in Appendex A of book "Tutorial: Creating an LLVM Backend for the Cpu0 Architecture" as follows.

```
1-160-136-173:tools Jonathan$ pwd
/Users/Jonathan/llvm/test/src/tools
1-160-136-173:tools Jonathan$ ls
...
lld             llvm-config     llvm-extract    llvm-nm         llvm-stress   obj2yaml
```

Next, setup Cpu0 backend as follows,

```
1-160-136-173:Cpu0 Jonathan$ cd ../../../tools/lld/lib/ReaderWriter/ELF/
1-160-136-173:ELF Jonathan$ pwd
/Users/Jonathan/llvm/test/src/tools/lld/lib/ReaderWriter/ELF
1-160-136-173:ELF Jonathan$ cp -rf ~/test/lbt/exlbt/lld/* .
1-160-136-173:ELF Jonathan$ mv Reference.h ../../../include/lld/Core/.
```

Finally, update llvm-objdump to support converting ELF file to Hex file as follows,

[3] http://llvm.org/releases/download.html#3.5

```
1-160-136-173:ELF Jonathan$ cd ../../../../llvm-objdump/
1-160-136-173:llvm-objdump Jonathan$ pwd
/Users/Jonathan/llvm/test/src/tools/llvm-objdump
1-160-136-173:llvm-objdump Jonathan$ cp -rf ~/test/lbt/exlbt/llvm-objdump/* .
```

Now, build lld with Cpu0 backend as follows,

```
1-160-136-173:cmake_debug_build Jonathan$ cmake -DCMAKE_CXX_COMPILER=clang++ -
DCMAKE_C_COMPILER=clang -DCMAKE_CXX_FLAGS=-std=c++11 -DCMAKE_BUILD_TYPE=Debug
-G "Xcode" ../src
...
-- Targeting Cpu0
...
-- Configuring done
-- Generating done
-- Build files have been written to: /Users/Jonathan/llvm/test/cmake_debug_build
```

If using VM (guest machine is Linux) or Linux, build as follows,

```
[Gamma@localhost cmake_debug_build]$ cmake -DCMAKE_CXX_COMPILER=g++ -
DCMAKE_C_COMPILER=gcc -DCMAKE_CXX_FLAGS=-std=c++11 -DCMAKE_BUILD_TYPE=Debug
-G "Unix Makefiles" ../src
...
-- Targeting Cpu0
...
-- Configuring done
-- Generating done
-- Build files have been written to: /home/cschen/llvm/test/cmake_debug_build
```

2.2.2 Cpu0 backend souce code

The code added on lld to support Cpu0 ELF as follows,

exlbt/lld/CMakeLists.txt

```
target_link_libraries(lldELF
  ...
  lldCpu0ELFTarget
  lldCpu0elELFTarget
  )
```

exlbt/lld/Atoms.h

```
class SimpleELFDefinedAtom : public SimpleDefinedAtom {
  ...
  void addReferenceELF_Cpu0(uint16_t relocType, uint64_t off, const Atom *t,
                            Reference::Addend a) {
    this->addReferenceELF(Reference::KindArch::Cpu0, relocType, off, t, a);
  }
}
```

exlbt/lld/ELFFile.h

```
template <class ELFT> Reference::KindArch ELFFile<ELFT>::kindArch() {
  switch (_objFile->getHeader()->e_machine) {
  ...
  case llvm::ELF::EM_CPU0:
    return Reference::KindArch::Cpu0;
  case llvm::ELF::EM_CPU0_LE:
    return Reference::KindArch::Cpu0el;
  ...
}
```

exlbt/lld/ELFLinkingContext.cpp

```
uint16_t ELFLinkingContext::getOutputMachine() const {
  switch (getTriple().getArch()) {
  ...
  case llvm::Triple::cpu0:
    return llvm::ELF::EM_CPU0;
  case llvm::Triple::cpu0el:
    return llvm::ELF::EM_CPU0_LE;
  ...
  }
}
...
std::unique_ptr<ELFLinkingContext>
ELFLinkingContext::create(llvm::Triple triple) {
  switch (triple.getArch()) {
  ...
  case llvm::Triple::cpu0:
    return std::unique_ptr<ELFLinkingContext>(
        new lld::elf::Cpu0LinkingContext(triple));
  case llvm::Triple::cpu0el:
    return std::unique_ptr<ELFLinkingContext>(
        new lld::elf::Cpu0elLinkingContext(triple));
}
```

exlbt/lld/Targets.h

```
#include "Cpu0/Cpu0Target.h"
#include "Cpu0el/Cpu0Target.h"
```

exlbt/lld/Reference.h

```
enum class KindArch {
  ...
  Cpu0    = 98,
  Cpu0el  = 99
};
```

exlbt/lld/Cpu0/CMakeLists.txt

```
add_lld_library(lldCpu0ELFTarget
  Cpu0LinkingContext.cpp
  Cpu0TargetHandler.cpp
  Cpu0RelocationHandler.cpp
  Cpu0RelocationPass.cpp
  )

target_link_libraries(lldCpu0ELFTarget ${cmake_2_8_12_INTERFACE}
  lldCore
  )
```

exlbt/lld/Cpu0/Cpu0DynamicLibraryWriter.h

```
//===- lib/ReaderWriter/ELF/Cpu0/Cpu0DynamicLibraryWriter.h ---------------===//
//
//                             The LLVM Linker
//
// This file is distributed under the University of Illinois Open Source
// License. See LICENSE.TXT for details.
//
//===----------------------------------------------------------------------===//
#ifndef Cpu0_DYNAMIC_LIBRARY_WRITER_H
#define Cpu0_DYNAMIC_LIBRARY_WRITER_H

#include "DynamicLibraryWriter.h"
#include "Cpu0LinkingContext.h"

namespace lld {
namespace elf {

template <class ELFT>
class Cpu0DynamicLibraryWriter : public DynamicLibraryWriter<ELFT> {
public:
  Cpu0DynamicLibraryWriter(Cpu0LinkingContext &context,
                           Cpu0TargetLayout<ELFT> &layout);

protected:
  // Add any runtime files and their atoms to the output
  virtual bool createImplicitFiles(std::vector<std::unique_ptr<File>> &);

  virtual void finalizeDefaultAtomValues() {
    return DynamicLibraryWriter<ELFT>::finalizeDefaultAtomValues();
  }

  virtual void addDefaultAtoms() {
    return DynamicLibraryWriter<ELFT>::addDefaultAtoms();
  }

private:
  class GOTFile : public SimpleFile {
  public:
    GOTFile(const ELFLinkingContext &eti) : SimpleFile("GOTFile") {}
    llvm::BumpPtrAllocator _alloc;
  };
```

```
  std::unique_ptr<GOTFile> _gotFile;
  Cpu0LinkingContext &_context;
  Cpu0TargetLayout<ELFT> &_cpu0Layout;
};

template <class ELFT>
Cpu0DynamicLibraryWriter<ELFT>::Cpu0DynamicLibraryWriter(
    Cpu0LinkingContext &context, Cpu0TargetLayout<ELFT> &layout)
    : DynamicLibraryWriter<ELFT>(context, layout),
      _gotFile(new GOTFile(context)), _context(context), _cpu0Layout(layout) {
}

template <class ELFT>
bool Cpu0DynamicLibraryWriter<ELFT>::createImplicitFiles(
    std::vector<std::unique_ptr<File>> &result) {
  DynamicLibraryWriter<ELFT>::createImplicitFiles(result);
  _gotFile->addAtom(*new (_gotFile->_alloc) GLOBAL_OFFSET_TABLEAtom(*_gotFile));
  _gotFile->addAtom(*new (_gotFile->_alloc) DYNAMICAtom(*_gotFile));
  result.push_back(std::move(_gotFile));
  return true;
}

} // namespace elf
} // namespace lld

#endif
```

exlbt/lld/Cpu0/Cpu0ExecutableWriter.h

```
//===- lib/ReaderWriter/ELF/Cpu0/Cpu0ExecutableWriter.h -------------------===//
//
//                             The LLVM Linker
//
// This file is distributed under the University of Illinois Open Source
// License. See LICENSE.TXT for details.
//
//===----------------------------------------------------------------------===//
#ifndef Cpu0_EXECUTABLE_WRITER_H
#define Cpu0_EXECUTABLE_WRITER_H

#include "ExecutableWriter.h"
#include "Cpu0LinkingContext.h"

namespace lld {
namespace elf {

template <class ELFT>
class Cpu0ExecutableWriter : public ExecutableWriter<ELFT> {
public:
  Cpu0ExecutableWriter(Cpu0LinkingContext &context,
                       Cpu0TargetLayout<ELFT> &layout);

protected:
  // Add any runtime files and their atoms to the output
  virtual bool createImplicitFiles(std::vector<std::unique_ptr<File>> &);
```

```
  virtual void finalizeDefaultAtomValues() {
    return ExecutableWriter<ELFT>::finalizeDefaultAtomValues();
  }

  virtual void addDefaultAtoms() {
    return ExecutableWriter<ELFT>::addDefaultAtoms();
  }

private:
  class GOTFile : public SimpleFile {
  public:
    GOTFile(const ELFLinkingContext &eti) : SimpleFile("GOTFile") {}
    llvm::BumpPtrAllocator _alloc;
  };

  std::unique_ptr<GOTFile> _gotFile;
  Cpu0LinkingContext &_context;
  Cpu0TargetLayout<ELFT> &_cpu0Layout;
};

template <class ELFT>
Cpu0ExecutableWriter<ELFT>::Cpu0ExecutableWriter(
    Cpu0LinkingContext &context, Cpu0TargetLayout<ELFT> &layout)
    : ExecutableWriter<ELFT>(context, layout), _gotFile(new GOTFile(context)),
      _context(context), _cpu0Layout(layout) {}

template <class ELFT>
bool Cpu0ExecutableWriter<ELFT>::createImplicitFiles(
    std::vector<std::unique_ptr<File>> &result) {
  ExecutableWriter<ELFT>::createImplicitFiles(result);
  _gotFile->addAtom(*new (_gotFile->_alloc) GLOBAL_OFFSET_TABLEAtom(*_gotFile));
  if (_context.isDynamic())
    _gotFile->addAtom(*new (_gotFile->_alloc) DYNAMICAtom(*_gotFile));
  result.push_back(std::move(_gotFile));
  return true;
}

} // namespace elf
} // namespace lld

#endif
```

exlbt/lld/Cpu0/Cpu0LinkingContext.h

```
//===- lib/ReaderWriter/ELF/Cpu0/Cpu0LinkingContext.h ---------------===//
//
//                             The LLVM Linker
//
// This file is distributed under the University of Illinois Open Source
// License. See LICENSE.TXT for details.
//
//===--------------------------------------------------------------------===//

#ifndef LLD_READER_WRITER_ELF_CPU0_CPU0_LINKING_CONTEXT_H
#define LLD_READER_WRITER_ELF_CPU0_CPU0_LINKING_CONTEXT_H

#include "Cpu0TargetHandler.h"
```

```
#include "lld/ReaderWriter/ELFLinkingContext.h"

#include "llvm/Object/ELF.h"
#include "llvm/Support/ELF.h"

namespace lld {
namespace elf {

/// \brief Cpu0 internal references.
enum {
  /// \brief The 32 bit index of the relocation in the got this reference refers
  /// to.
  LLD_R_CPU0_GOTRELINDEX = 1024,
};

class Cpu0LinkingContext final : public ELFLinkingContext {
public:
  Cpu0LinkingContext(llvm::Triple triple)
      : ELFLinkingContext(triple, std::unique_ptr<TargetHandlerBase>(
                                      new Cpu0TargetHandler(*this))) {}

//  bool isLittleEndian() const override { return false; }

  void addPasses(PassManager &) override;

  uint64_t getBaseAddress() const override {
    if (_baseAddress == 0)
      return 0x000000;
    return _baseAddress;
  }

  bool isDynamicRelocation(const DefinedAtom &,
                           const Reference &r) const override {
    if (r.kindNamespace() != Reference::KindNamespace::ELF)
      return false;
    assert(r.kindArch() == Reference::KindArch::Cpu0);
    switch (r.kindValue()) {
    case llvm::ELF::R_CPU0_GLOB_DAT:
      return true;
    default:
      return false;
    }
  }

  virtual bool isPLTRelocation(const DefinedAtom &,
                               const Reference &r) const override {
    if (r.kindNamespace() != Reference::KindNamespace::ELF)
      return false;
    assert(r.kindArch() == Reference::KindArch::Cpu0);
    switch (r.kindValue()) {
    case llvm::ELF::R_CPU0_JUMP_SLOT:
    case llvm::ELF::R_CPU0_RELGOT:
      return true;
    default:
      return false;
    }
  }
```

```
  /// \brief Cpu0 has two relative relocations
  /// a) for supporting relative relocs - R_CPU0_RELGOT
  bool isRelativeReloc(const Reference &r) const override {
    if (r.kindNamespace() != Reference::KindNamespace::ELF)
      return false;
    assert(r.kindArch() == Reference::KindArch::Cpu0);
    switch (r.kindValue()) {
    case llvm::ELF::R_CPU0_RELGOT:
      return true;
    default:
      return false;
    }
  }

  bool isStaticExecutable() const { return _isStaticExecutable; }
};
} // end namespace elf
} // end namespace lld

#endif
```

exlbt/lld/Cpu0/Cpu0LinkingContext.cpp

```
//===- lib/ReaderWriter/ELF/Cpu0/Cpu0LinkingContext.cpp ---------------===//
//
//                             The LLVM Linker
//
// This file is distributed under the University of Illinois Open Source
// License. See LICENSE.TXT for details.
//
//===--------------------------------------------------------------------===//

#include "Cpu0LinkingContext.h"
#include "Cpu0RelocationPass.h"

using namespace lld;

void elf::Cpu0LinkingContext::addPasses(PassManager &pm) {
  auto pass = createCpu0RelocationPass(*this);
  if (pass)
    pm.add(std::move(pass));
  ELFLinkingContext::addPasses(pm);
}
```

exlbt/lld/Cpu0/Cpu0RelocationHandler.h

```
//===- lib/ReaderWriter/ELF/Cpu0/Cpu0RelocationHandler.h --------------===//
//
//                             The LLVM Linker
//
// This file is distributed under the University of Illinois Open Source
// License. See LICENSE.TXT for details.
//
//===--------------------------------------------------------------------===//
```

```
#ifndef CPU0_RELOCATION_HANDLER_H
#define CPU0_RELOCATION_HANDLER_H

#include "Cpu0TargetHandler.h"

namespace lld {
namespace elf {
typedef llvm::object::ELFType<llvm::support::big, 2, false> Cpu0ELFType;
class Cpu0LinkingContext;

template <class ELFT> class Cpu0TargetLayout;

class Cpu0TargetRelocationHandler final
    : public TargetRelocationHandler<Cpu0ELFType> {
public:
  Cpu0TargetRelocationHandler(Cpu0TargetLayout<Cpu0ELFType> &layout,
                              Cpu0LinkingContext &context,
                              ELFLinkingContext &targetInfo)
      : TargetRelocationHandler<Cpu0ELFType>(targetInfo),
        _tlsSize(0), _cpu0Layout(layout),
        _context(context) {}

  std::error_code applyRelocation(ELFWriter &, llvm::FileOutputBuffer &,
                                  const lld::AtomLayout &,
                                  const Reference &) const override;

private:
  // Cached size of the TLS segment.
  mutable uint64_t _tlsSize;
  Cpu0TargetLayout<Cpu0ELFType> &_cpu0Layout;
  Cpu0LinkingContext &_context;
};

} // end namespace elf
} // end namespace lld

#endif // Cpu0_RELOCATION_HANDLER_H
```

exlbt/lld/Cpu0/Cpu0RelocationHandler.cpp

```
//===- lib/ReaderWriter/ELF/Cpu0/Cpu0RelocationHandler.cpp ------------===//
//
//                             The LLVM Linker
//
// This file is distributed under the University of Illinois Open Source
// License. See LICENSE.TXT for details.
//
//===--------------------------------------------------------------------===//

#include "Cpu0TargetHandler.h"
#include "Cpu0LinkingContext.h"
#include "llvm/Object/ObjectFile.h"
#include "llvm/Support/raw_ostream.h"

using namespace lld;
using namespace elf;
```

```
using namespace llvm;
using namespace object;

static bool error(std::error_code ec) {
  if (!ec) return false;

  outs() << "Cpu0RelocationHandler.cpp : error reading file: "
         << ec.message() << ".\n";
  outs().flush();
  return true;
}

namespace {
/// \brief R_CPU0_HI16 - word64: (S + A) >> 16
void relocHI16(uint8_t *location, uint64_t P, uint64_t S, int64_t A) {
 // Don't know why A, ref.addend(), = 9
  uint32_t result = (uint32_t)(S >> 16);
  *reinterpret_cast<llvm::support::ubig32_t *>(location) =
      result |
      (uint32_t) * reinterpret_cast<llvm::support::ubig32_t *>(location);
}

void relocLO16(uint8_t *location, uint64_t P, uint64_t S, uint64_t A) {
 // Don't know why A, ref.addend(), = 9
  uint32_t result = (uint32_t)(S & 0x0000ffff);
  *reinterpret_cast<llvm::support::ubig32_t *>(location) =
      result |
      (uint32_t) * reinterpret_cast<llvm::support::ubig32_t *>(location);
}

/// \brief R_CPU0_GOT16 - word32: S
void relocGOT16(uint8_t *location, uint64_t P, uint64_t S, int64_t A) {
  uint32_t result = (uint32_t)(S);
  *reinterpret_cast<llvm::support::ubig32_t *>(location) =
      result |
      (uint32_t) * reinterpret_cast<llvm::support::ubig32_t *>(location);
}

/// \brief R_CPU0_PC24 - word32: S + A - P
void relocPC24(uint8_t *location, uint64_t P, uint64_t S, int64_t A) {
  uint32_t result = (uint32_t)(S  - P);
  uint32_t machinecode = (uint32_t) *
                         reinterpret_cast<llvm::support::ubig32_t *>(location);
  uint32_t opcode = (machinecode & 0xff000000);
  uint32_t offset = (machinecode & 0x00ffffff);
  *reinterpret_cast<llvm::support::ubig32_t *>(location) =
      (((result + offset) & 0x00ffffff) | opcode);
}

/// \brief R_CPU0_32 - word32:  S
void reloc32(uint8_t *location, uint64_t P, uint64_t S, int64_t A) {
  int32_t result = (uint32_t)(S);
  *reinterpret_cast<llvm::support::ubig32_t *>(location) =
      result |
      (uint32_t) * reinterpret_cast<llvm::support::ubig32_t *>(location);
  // TODO: Make sure that the result zero extends to the 64bit value.
}
} // end anon namespace
```

```
#ifdef DLINKER
class Cpu0SoPlt {
private:
  uint32_t funAddr[100];
  int funAddrSize = 0;
public:
  Cpu0TargetLayout<Cpu0ELFType> *_cpu0Layout;
  void createFunAddr(Cpu0TargetLayout<Cpu0ELFType> *cpu0Layout,
                     llvm::FileOutputBuffer &buf);
  // Return function index, 1: 1st function appear on section .text of .so.
  //   2: 2nd function ...
  // For example: 3 functions _Z2laii, _Z3fooii and _Z3barv. 1: is _Z2laii
  //   2 is _Z3fooii, 3: is _Z3barv.
  int getDynFunIndexByTargetAddr(uint64_t fAddr);
};

void Cpu0SoPlt::createFunAddr(Cpu0TargetLayout<Cpu0ELFType> *cpu0Layout,
                              llvm::FileOutputBuffer &buf) {
  auto dynsymSection = cpu0Layout->
                       findOutputSection(".dynsym");
  uint64_t dynsymFileOffset, dynsymSize;
  if (dynsymSection) {
    dynsymFileOffset = dynsymSection->fileOffset();
    dynsymSize = dynsymSection->memSize();
    uint8_t *atomContent = buf.getBufferStart() + dynsymFileOffset;
    for (uint64_t i = 4; i < dynsymSize; i += 16) {
      funAddr[funAddrSize] =
        *reinterpret_cast<llvm::support::ubig32_t*>((uint32_t*)
        (atomContent + i));
      funAddrSize++;
    }
  }
}

int Cpu0SoPlt::getDynFunIndexByTargetAddr(uint64_t fAddr) {
  for (int i = 0; i < funAddrSize; i++) {
    // Below statement fix the issue that both __tls_get_addr and first
    // function has the same file offset 0 issue.
    if (i < (funAddrSize-1) && funAddr[i] == funAddr[i+1])
      continue;

    if (fAddr == funAddr[i]) {
      return i;
    }
  }
  return -1;
}

Cpu0SoPlt cpu0SoPlt;
#endif // DLINKER

std::error_code Cpu0TargetRelocationHandler::applyRelocation(
    ELFWriter &writer, llvm::FileOutputBuffer &buf, const lld::AtomLayout &atom,
    const Reference &ref) const {
#ifdef DLINKER
  static bool firstTime = true;
  std::string soName("libfoobar.cpu0.so");
  int idx = 0;
```

```
  if (firstTime) {
    if (this->_context.getOutputELFType() == llvm::ELF::ET_DYN) {
      cpu0SoPlt.createFunAddr(&(this->_cpu0Layout), buf);
    }
    else if (this->_context.getOutputELFType() == llvm::ELF::ET_EXEC &&
             !this->_context.isStaticExecutable()) {
      cpu0SoPlt.createFunAddr(&(this->_cpu0Layout), buf);
    }
    firstTime = false;
  }
#endif // DLINKER
  uint8_t *atomContent = buf.getBufferStart() + atom._fileOffset;
  uint8_t *location = atomContent + ref.offsetInAtom();
  uint64_t targetVAddress = writer.addressOfAtom(ref.target());
  uint64_t relocVAddress = atom._virtualAddr + ref.offsetInAtom();
#if 1 // For case R_CPU0_GOT16:
//  auto gotAtomIter = _context.getTargetHandler<Cpu0ELFType>().targetLayout().
//                     findAbsoluteAtom("_GLOBAL_OFFSET_TABLE_");
//  uint64_t globalOffsetTableAddress = writer.addressOfAtom(*gotAtomIter);
// .got.plt start from _GLOBAL_OFFSET_TABLE_
  auto gotpltSection = _cpu0Layout.findOutputSection(".got.plt");
  uint64_t gotPltFileOffset;
  if (gotpltSection)
    gotPltFileOffset = gotpltSection->fileOffset();
  else
    gotPltFileOffset = 0;
#endif

  if (ref.kindNamespace() != Reference::KindNamespace::ELF)
    return std::error_code();
  assert(ref.kindArch() == Reference::KindArch::Cpu0);
  switch (ref.kindValue()) {
  case R_CPU0_NONE:
    break;

  case R_CPU0_HI16:
    relocHI16(location, relocVAddress, targetVAddress, ref.addend());
    break;
  case R_CPU0_LO16:
    relocLO16(location, relocVAddress, targetVAddress, ref.addend());
    break;
#if 0 // Not support yet
  case R_CPU0_GOT16:
#if 1
    idx = cpu0SoPlt.getDynFunIndexByTargetAddr(targetVAddress);
    relocGOT16(location, relocVAddress, idx, ref.addend());
#else
    relocGOT16(location, relocVAddress, (targetVAddress - gotPltFileOffset),
               ref.addend());
#endif
    break;
#endif
  case R_CPU0_PC24:
    relocPC24(location, relocVAddress, targetVAddress, ref.addend());
    break;
#ifdef DLINKER
  case R_CPU0_CALL16:
  // offset at _GLOBAL_OFFSET_TABLE_ and $gp point to _GLOBAL_OFFSET_TABLE_.
```

```
    idx = cpu0SoPlt.getDynFunIndexByTargetAddr(targetVAddress);
    reloc32(location, relocVAddress, idx*0x04+16, ref.addend());
    break;
#endif // DLINKER
  case R_CPU0_32:
    reloc32(location, relocVAddress, targetVAddress, ref.addend());
    break;

  // Runtime only relocations. Ignore here.
  case R_CPU0_JUMP_SLOT:
  case R_CPU0_GLOB_DAT:
    break;
  default:
    unhandledReferenceType(*atom._atom, ref);
  }

  return std::error_code();
}
```

exlbt/lld/Cpu0/Cpu0RelocationPass.h

```
//===- lib/ReaderWriter/ELF/Cpu0/Cpu0RelocationPass.h ------------------===//
//
//                             The LLVM Linker
//
// This file is distributed under the University of Illinois Open Source
// License. See LICENSE.TXT for details.
//
//===---------------------------------------------------------------------===//
///
/// \file
/// \brief Declares the relocation processing pass for Cpu0. This includes
///   GOT and PLT entries, TLS, COPY, and ifunc.
///
//===---------------------------------------------------------------------===//

#ifndef LLD_READER_WRITER_ELF_CPU0_CPU0_RELOCATION_PASS_H
#define LLD_READER_WRITER_ELF_CPU0_CPU0_RELOCATION_PASS_H

#include <memory>

namespace lld {
class Pass;
namespace elf {
class Cpu0LinkingContext;

/// \brief Create Cpu0 relocation pass for the given linking context.
std::unique_ptr<Pass>
createCpu0RelocationPass(const Cpu0LinkingContext &);
}
}

#endif
```

exlbt/lld/Cpu0/Cpu0RelocationPass.cpp

```
//===- lib/ReaderWriter/ELF/Cpu0/Cpu0RelocationPass.cpp ---------------===//
//
//                             The LLVM Linker
//
// This file is distributed under the University of Illinois Open Source
// License. See LICENSE.TXT for details.
//
//===--------------------------------------------------------------------===//
///
/// \file
/// \brief Defines the relocation processing pass for Cpu0. This includes
///   GOT and PLT entries, TLS, COPY, and ifunc.
///
/// This is based on section 4.4.1 of the AMD64 ABI (no stable URL as of Oct,
/// 2013).
///
/// This also includes aditional behaivor that gnu-ld and gold implement but
/// which is not specified anywhere.
///
//===--------------------------------------------------------------------===//

#include "Atoms.h"
#include "Cpu0RelocationPass.h"
#include "Cpu0LinkingContext.h"

#include "lld/Core/Simple.h"

#include "llvm/ADT/DenseMap.h"


using namespace lld;
using namespace lld::elf;
using namespace llvm::ELF;

namespace {
// .plt value (entry 0)
const uint8_t cpu0BootAtomContent[16] = {
  0x36, 0xff, 0xff, 0xfc, // jmp start
  0x36, 0x00, 0x00, 0x04, // jmp 4
  0x36, 0xff, 0xff, 0xfc, // jmp ISR
  0x36, 0xff, 0xff, 0xfc // jmp -4
};

#ifdef DLINKER
// .got values
const uint8_t cpu0GotAtomContent[16] = { 0 };

// .plt value (entry 0)
const uint8_t cpu0Plt0AtomContent[16] = {
  0x02, 0xeb, 0x00, 0x04, // st $lr, $zero, reloc-index ($gp)
  0x02, 0xcb, 0x00, 0x08, // st $fp, $zero, reloc-index ($gp)
  0x02, 0xdb, 0x00, 0x0c, // st $sp, $zero, reloc-index ($gp)
  0x36, 0xff, 0xff, 0xfc  // jmp dynamic_linker
};

// .plt values (other entries)
```

```
const uint8_t cpu0PltAtomContent[16] = {
  0x01, 0x6b, 0x00, 0x10, // ld $t9, 0x10($gp) (0x10($gp) point to plt0
  0x3c, 0x60, 0x00, 0x00, // ret $t9 // jump to Cpu0.Stub
  0x00, 0x00, 0x00, 0x00, // nop
  0x00, 0x00, 0x00, 0x00  // nop
};
#endif // DLINKER

/// boot record
class Cpu0BootAtom : public PLT0Atom {
public:
  Cpu0BootAtom(const File &f) : PLT0Atom(f) {
#ifndef NDEBUG
    _name = ".PLT0";
#endif
  }
  virtual ArrayRef<uint8_t> rawContent() const {
    return ArrayRef<uint8_t>(cpu0BootAtomContent, 16);
  }
};

#ifdef DLINKER
/// \brief Atoms that are used by Cpu0 dynamic linking
class Cpu0GOTAtom : public GOTAtom {
public:
  Cpu0GOTAtom(const File &f, StringRef secName) : GOTAtom(f, secName) {}

  ArrayRef<uint8_t> rawContent() const override {
    return ArrayRef<uint8_t>(cpu0GotAtomContent, 16);
  }
};

class Cpu0PLT0Atom : public PLT0Atom {
public:
  Cpu0PLT0Atom(const File &f) : PLT0Atom(f) {
#ifndef NDEBUG
    _name = ".PLT0";
#endif
  }
  ArrayRef<uint8_t> rawContent() const override {
    return ArrayRef<uint8_t>(cpu0Plt0AtomContent, 16);
  }
};

class Cpu0PLTAtom : public PLTAtom {
public:
  Cpu0PLTAtom(const File &f, StringRef secName) : PLTAtom(f, secName) {}

  ArrayRef<uint8_t> rawContent() const override {
    return ArrayRef<uint8_t>(cpu0PltAtomContent, 16);
  }
};
#endif // DLINKER

class ELFPassFile : public SimpleFile {
public:
  ELFPassFile(const ELFLinkingContext &eti) : SimpleFile("ELFPassFile") {
    setOrdinal(eti.getNextOrdinalAndIncrement());
```

```
  }

  llvm::BumpPtrAllocator _alloc;
};

/// \brief CRTP base for handling relocations.
template <class Derived> class RelocationPass : public Pass {
  /// \brief Handle a specific reference.
  void handleReference(const DefinedAtom &atom, const Reference &ref) {
    if (ref.kindNamespace() != Reference::KindNamespace::ELF)
      return;
    assert(ref.kindArch() == Reference::KindArch::Cpu0);
    switch (ref.kindValue()) {
    case R_CPU0_CALL16:
      static_cast<Derived *>(this)->handlePLT32(ref);
      break;

    case R_CPU0_PC24:
      static_cast<Derived *>(this)->handlePlain(ref);
      break;
    }
  }

protected:
#ifdef DLINKER
  /// \brief get the PLT entry for a given IFUNC Atom.
  ///
  /// If the entry does not exist. Both the GOT and PLT entry is created.
  const PLTAtom *getIFUNCPLTEntry(const DefinedAtom *da) {
    auto plt = _pltMap.find(da);
    if (plt != _pltMap.end())
      return plt->second;
    auto ga = new (_file._alloc) Cpu0GOTAtom(_file, ".got.plt");
    ga->addReferenceELF_Cpu0(R_CPU0_RELGOT, 0, da, 0);
    auto pa = new (_file._alloc) Cpu0PLTAtom(_file, ".plt");
    pa->addReferenceELF_Cpu0(R_CPU0_PC24, 2, ga, -4);
#ifndef NDEBUG
    ga->_name = "__got_ifunc_";
    ga->_name += da->name();
    pa->_name = "__plt_ifunc_";
    pa->_name += da->name();
#endif
    _gotMap[da] = ga;
    _pltMap[da] = pa;
    _gotVector.push_back(ga);
    _pltVector.push_back(pa);
    return pa;
  }
#endif // DLINKER

  /// \brief Redirect the call to the PLT stub for the target IFUNC.
  ///
  /// This create a PLT and GOT entry for the IFUNC if one does not exist. The
  /// GOT entry and a IRELATIVE relocation to the original target resolver.
  std::error_code handleIFUNC(const Reference &ref) {
    auto target = dyn_cast_or_null<const DefinedAtom>(ref.target());
#ifdef DLINKER
    if (target && target->contentType() == DefinedAtom::typeResolver)
```

```
      const_cast<Reference &>(ref).setTarget(getIFUNCPLTEntry(target));
#endif // DLINKER
    return std::error_code();
  }

  /// \brief Create a GOT entry for the TP offset of a TLS atom.
  const GOTAtom *getGOTTPOFF(const Atom *atom) {
    auto got = _gotMap.find(atom);
    if (got == _gotMap.end()) {
      auto g = new (_file._alloc) Cpu0GOTAtom(_file, ".got");
      g->addReferenceELF_Cpu0(R_CPU0_TLS_TPREL32, 0, atom, 0);
#ifndef NDEBUG
      g->_name = "__got_tls_";
      g->_name += atom->name();
#endif
      _gotMap[atom] = g;
      _gotVector.push_back(g);
      return g;
    }
    return got->second;
  }

  /// \brief Create a GOT entry containing 0.
  const GOTAtom *getNullGOT() {
    if (!_null) {
      _null = new (_file._alloc) Cpu0GOTAtom(_file, ".got.plt");
#ifndef NDEBUG
      _null->_name = "__got_null";
#endif
    }
    return _null;
  }

  const GOTAtom *getGOT(const DefinedAtom *da) {
    auto got = _gotMap.find(da);
    if (got == _gotMap.end()) {
      auto g = new (_file._alloc) Cpu0GOTAtom(_file, ".got");
      g->addReferenceELF_Cpu0(R_CPU0_32, 0, da, 0);
#ifndef NDEBUG
      g->_name = "__got_";
      g->_name += da->name();
#endif
      _gotMap[da] = g;
      _gotVector.push_back(g);
      return g;
    }
    return got->second;
  }

public:
  RelocationPass(const ELFLinkingContext &ctx)
      : _file(ctx), _ctx(ctx), _null(nullptr), _PLT0(nullptr), _got0(nullptr),
        _boot(new Cpu0BootAtom(_file)) {}

  /// \brief Do the pass.
  ///
  /// The goal here is to first process each reference individually. Each call
  /// to handleReference may modify the reference itself and/or create new
```

```
  /// atoms which must be stored in one of the maps below.
  ///
  /// After all references are handled, the atoms created during that are all
  /// added to mf.
  void perform(std::unique_ptr<MutableFile> &mf) override {
    ScopedTask task(getDefaultDomain(), "Cpu0 GOT/PLT Pass");
    // Process all references.
    for (const auto &atom : mf->defined())
      for (const auto &ref : *atom)
        handleReference(*atom, *ref);

    // Add all created atoms to the link.
    uint64_t ordinal = 0;
    if (_ctx.getOutputELFType() == llvm::ELF::ET_EXEC) {
      MutableFile::DefinedAtomRange atomRange = mf->definedAtoms();
      auto it = atomRange.begin();
      bool find = false;
      for (it = atomRange.begin(); it < atomRange.end(); it++) {
        if ((*it)->name() == "start") {
          find = true;
          break;
        }
      }
      assert(find && "not found start\n");
      _boot->addReferenceELF_Cpu0(R_CPU0_PC24, 0, *it, -3);
      find = false;
      for (it = atomRange.begin(); it < atomRange.end(); it++) {
        if ((*it)->name() == "ISR") {
          find = true;
          break;
        }
      }
      assert(find && "not found ISR\n");
      _boot->addReferenceELF_Cpu0(R_CPU0_PC24, 8, *it, -3);
      _boot->setOrdinal(ordinal++);
      mf->addAtom(*_boot);
    }
#ifdef DLINKER
    if (_PLT0) {
      MutableFile::DefinedAtomRange atomRange = mf->definedAtoms();
      auto it = atomRange.begin();
      bool find = false;
      for (it = atomRange.begin(); it < atomRange.end(); it++) {
        if ((*it)->name() == "_Z14dynamic_linkerv") {
          find = true;
          break;
        }
      }
      assert(find && "Cannot find _Z14dynamic_linkerv()");
      _PLT0->addReferenceELF_Cpu0(R_CPU0_PC24, 12, *it, -3);
      _PLT0->setOrdinal(ordinal++);
      mf->addAtom(*_PLT0);
    }
    for (auto &plt : _pltVector) {
      plt->setOrdinal(ordinal++);
      mf->addAtom(*plt);
    }
    if (_null) {
```

```
      _null->setOrdinal(ordinal++);
      mf->addAtom(*_null);
    }
    if (_PLT0) {
      _got0->setOrdinal(ordinal++);
      mf->addAtom(*_got0);
    }
    for (auto &got : _gotVector) {
      got->setOrdinal(ordinal++);
      mf->addAtom(*got);
    }
    for (auto obj : _objectVector) {
      obj->setOrdinal(ordinal++);
      mf->addAtom(*obj);
    }
#endif // DLINKER
  }

protected:
  /// \brief Owner of all the Atoms created by this pass.
  ELFPassFile _file;
  const ELFLinkingContext &_ctx;

  /// \brief Map Atoms to their GOT entries.
  llvm::DenseMap<const Atom *, GOTAtom *> _gotMap;

  /// \brief Map Atoms to their PLT entries.
  llvm::DenseMap<const Atom *, PLTAtom *> _pltMap;

  /// \brief Map Atoms to their Object entries.
  llvm::DenseMap<const Atom *, ObjectAtom *> _objectMap;

  /// \brief the list of GOT/PLT atoms
  std::vector<GOTAtom *> _gotVector;
  std::vector<PLTAtom *> _pltVector;
  std::vector<ObjectAtom *> _objectVector;
  PLT0Atom *_boot;

  /// \brief GOT entry that is always 0. Used for undefined weaks.
  GOTAtom *_null;

  /// \brief The got and plt entries for .PLT0. This is used to call into the
  /// dynamic linker for symbol resolution.
  /// @{
  PLT0Atom *_PLT0;
  GOTAtom *_got0;
  /// @}
};

/// This implements the static relocation model. Meaning GOT and PLT entries are
/// not created for references that can be directly resolved. These are
/// converted to a direct relocation. For entries that do require a GOT or PLT
/// entry, that entry is statically bound.
///
/// TLS always assumes module 1 and attempts to remove indirection.
class StaticRelocationPass final
    : public RelocationPass<StaticRelocationPass> {
public:
```

```
  StaticRelocationPass(const elf::Cpu0LinkingContext &ctx)
      : RelocationPass(ctx) {}

  std::error_code handlePlain(const Reference &ref) { return handleIFUNC(ref); }

  std::error_code handlePLT32(const Reference &ref) {
    // __tls_get_addr is handled elsewhere.
    if (ref.target() && ref.target()->name() == "__tls_get_addr") {
      const_cast<Reference &>(ref).setKindValue(R_CPU0_NONE);
      return std::error_code();
    }
    // Static code doesn't need PLTs.
    const_cast<Reference &>(ref).setKindValue(R_CPU0_PC24);
    // Handle IFUNC.
    if (const DefinedAtom *da =
            dyn_cast_or_null<const DefinedAtom>(ref.target()))
      if (da->contentType() == DefinedAtom::typeResolver)
        return handleIFUNC(ref);
    return std::error_code();
  }

  std::error_code handleGOT(const Reference &ref) {
    if (isa<UndefinedAtom>(ref.target()))
      const_cast<Reference &>(ref).setTarget(getNullGOT());
    else if (const DefinedAtom *da = dyn_cast<const DefinedAtom>(ref.target()))
      const_cast<Reference &>(ref).setTarget(getGOT(da));
    return std::error_code();
  }
};

#ifdef DLINKER
class DynamicRelocationPass final
    : public RelocationPass<DynamicRelocationPass> {
public:
  DynamicRelocationPass(const elf::Cpu0LinkingContext &ctx)
      : RelocationPass(ctx) {}

  const PLT0Atom *getPLT0() {
    if (_PLT0)
      return _PLT0;
    // Fill in the null entry.
    getNullGOT();
    _PLT0 = new (_file._alloc) Cpu0PLT0Atom(_file);
    _got0 = new (_file._alloc) Cpu0GOTAtom(_file, ".got.plt");
#ifndef NDEBUG
    _got0->_name = "__got0";
#endif
    return _PLT0;
  }

  const PLTAtom *getPLTEntry(const Atom *a) {
    auto plt = _pltMap.find(a);
    if (plt != _pltMap.end())
      return plt->second;
    auto ga = new (_file._alloc) Cpu0GOTAtom(_file, ".got.plt");
    ga->addReferenceELF_Cpu0(R_CPU0_JUMP_SLOT, 0, a, 0);
    auto pa = new (_file._alloc) Cpu0PLTAtom(_file, ".plt");
    getPLT0();  // add _PLT0 and _got0
```

```
    // Set the starting address of the got entry to the second instruction in
    // the plt entry.
    ga->addReferenceELF_Cpu0(R_CPU0_32, 0, pa, 4);
#ifndef NDEBUG
    ga->_name = "__got_";
    ga->_name += a->name();
    pa->_name = "__plt_";
    pa->_name += a->name();
#endif
    _gotMap[a] = ga;
    _pltMap[a] = pa;
    _gotVector.push_back(ga);
    _pltVector.push_back(pa);
    return pa;
  }

#if 0 // Not support at this point
  const ObjectAtom *getObjectEntry(const SharedLibraryAtom *a) {
    auto obj = _objectMap.find(a);
    if (obj != _objectMap.end())
      return obj->second;

    auto oa = new (_file._alloc) ObjectAtom(_file);
    // This needs to point to the atom that we just created.
    oa->addReferenceELF_Cpu0(R_Cpu0_COPY, 0, oa, 0);

    oa->_name = a->name();
    oa->_size = a->size();

    _objectMap[a] = oa;
    _objectVector.push_back(oa);
    return oa;
  }
#endif

  std::error_code handlePlain(const Reference &ref) {
    if (!ref.target())
      return std::error_code();
    if (auto sla = dyn_cast<SharedLibraryAtom>(ref.target())) {
#if 0 // Not support at this point
      if (sla->type() == SharedLibraryAtom::Type::Data)
        const_cast<Reference &>(ref).setTarget(getObjectEntry(sla));
      else
#endif
      if (sla->type() == SharedLibraryAtom::Type::Code)
        const_cast<Reference &>(ref).setTarget(getPLTEntry(sla));
    } else
      return handleIFUNC(ref);
    return std::error_code();
  }

  std::error_code handlePLT32(const Reference &ref) {
    // Handle IFUNC.
    if (const DefinedAtom *da =
            dyn_cast_or_null<const DefinedAtom>(ref.target()))
      if (da->contentType() == DefinedAtom::typeResolver)
        return handleIFUNC(ref);
    if (isa<const SharedLibraryAtom>(ref.target())) {
```

```
      const_cast<Reference &>(ref).setTarget(getPLTEntry(ref.target()));
      // Turn this into a PC24 to the PLT entry.
    #if 1
      const_cast<Reference &>(ref).setKindValue(R_CPU0_PC24);
    #endif
    }
    return std::error_code();
  }

  const GOTAtom *getSharedGOT(const Atom *a) {
    auto got = _gotMap.find(a);
    if (got == _gotMap.end()) {
      auto g = new (_file._alloc) Cpu0GOTAtom(_file, ".got.dyn");
      g->addReferenceELF_Cpu0(R_CPU0_GLOB_DAT, 0, a, 0);
#ifndef NDEBUG
      g->_name = "__got_";
      g->_name += a->name();
#endif
      _gotMap[a] = g;
      _gotVector.push_back(g);
      return g;
    }
    return got->second;
  }

  std::error_code handleGOT(const Reference &ref) {
    if (const DefinedAtom *da = dyn_cast<const DefinedAtom>(ref.target()))
      const_cast<Reference &>(ref).setTarget(getGOT(da));
    // Handle undefined atoms in the same way as shared lib atoms: to be
    // resolved at run time.
    else if (isa<SharedLibraryAtom>(ref.target()) ||
             isa<UndefinedAtom>(ref.target()))
      const_cast<Reference &>(ref).setTarget(getSharedGOT(ref.target()));
    return std::error_code();
  }
};
#endif // DLINKER
} // end anon namespace

std::unique_ptr<Pass>
lld::elf::createCpu0RelocationPass(const Cpu0LinkingContext &ctx) {
  switch (ctx.getOutputELFType()) {
  case llvm::ELF::ET_EXEC:
  // when the output file is execution file: e.g. a.out
#ifdef DLINKER
    if (ctx.isDynamic())
    // when the a.out refer to shared object *.so
      return std::unique_ptr<Pass>(new DynamicRelocationPass(ctx));
    else
#endif // DLINKER
      return std::unique_ptr<Pass>(new StaticRelocationPass(ctx));
#ifdef DLINKER
  case llvm::ELF::ET_DYN:
  // when the output file is shared object: e.g. foobar.so
    return std::unique_ptr<Pass>(new DynamicRelocationPass(ctx));
#endif // DLINKER
  case llvm::ELF::ET_REL:
    return std::unique_ptr<Pass>();
```

```
  default:
    llvm_unreachable("Unhandled output file type");
  }
}
```

exlbt/lld/Cpu0/Cpu0LinkingContext.cpp

```
//===- lib/ReaderWriter/ELF/Cpu0/Cpu0LinkingContext.cpp ---------------===//
//
//                             The LLVM Linker
//
// This file is distributed under the University of Illinois Open Source
// License. See LICENSE.TXT for details.
//
//===----------------------------------------------------------------------===//

#include "Cpu0LinkingContext.h"
#include "Cpu0RelocationPass.h"

using namespace lld;

void elf::Cpu0LinkingContext::addPasses(PassManager &pm) {
  auto pass = createCpu0RelocationPass(*this);
  if (pass)
    pm.add(std::move(pass));
  ELFLinkingContext::addPasses(pm);
}
```

exlbt/lld/Cpu0/Cpu0Target.h

```
//===- lib/ReaderWriter/ELF/Cpu0/Cpu0Target.h -------------------------===//
//
//                             The LLVM Linker
//
// This file is distributed under the University of Illinois Open Source
// License. See LICENSE.TXT for details.
//
//===----------------------------------------------------------------------===//

#include "Cpu0LinkingContext.h"
```

exlbt/lld/Cpu0/Cpu0TargetHandler.h

```
//===- lib/ReaderWriter/ELF/Cpu0/Cpu0TargetHandler.h ------------------===//
//
//                             The LLVM Linker
//
// This file is distributed under the University of Illinois Open Source
// License. See LICENSE.TXT for details.
//
//===----------------------------------------------------------------------===//

#ifndef LLD_READER_WRITER_ELF_CPU0_CPU0_TARGET_HANDLER_H
```

```
#define LLD_READER_WRITER_ELF_CPU0_CPU0_TARGET_HANDLER_H

#include "Cpu0ELFFile.h"
#include "Cpu0ELFReader.h"
#include "Cpu0RelocationHandler.h"
#include "DefaultTargetHandler.h"
#include "TargetLayout.h"

#include "lld/Core/Simple.h"

#define DLINKER

namespace lld {
namespace elf {
typedef llvm::object::ELFType<llvm::support::big, 2, false> Cpu0ELFType;
class Cpu0LinkingContext;

template <class ELFT> class Cpu0TargetLayout : public TargetLayout<ELFT> {
public:
  Cpu0TargetLayout(Cpu0LinkingContext &context)
      : TargetLayout<ELFT>(context) {}
};

class Cpu0TargetHandler final
    : public DefaultTargetHandler<Cpu0ELFType> {
public:
  Cpu0TargetHandler(Cpu0LinkingContext &context);

  Cpu0TargetLayout<Cpu0ELFType> &getTargetLayout() override {
    return *(_cpu0TargetLayout.get());
  }

  void registerRelocationNames(Registry &registry) override;

  const Cpu0TargetRelocationHandler &getRelocationHandler() const override {
    return *(_cpu0RelocationHandler.get());
  }

  std::unique_ptr<Reader> getObjReader(bool atomizeStrings) override {
    return std::unique_ptr<Reader>(new Cpu0ELFObjectReader(atomizeStrings));
  }

  std::unique_ptr<Reader> getDSOReader(bool useShlibUndefines) override {
    return std::unique_ptr<Reader>(new Cpu0ELFDSOReader(useShlibUndefines));
  }

  std::unique_ptr<Writer> getWriter() override;

private:
  static const Registry::KindStrings kindStrings[];
  Cpu0LinkingContext &_context;
  std::unique_ptr<Cpu0TargetLayout<Cpu0ELFType>> _cpu0TargetLayout;
  std::unique_ptr<Cpu0TargetRelocationHandler> _cpu0RelocationHandler;
};

} // end namespace elf
} // end namespace lld
```

```
#endif
```

exlbt/lld/Cpu0/Cpu0TargetHandler.cpp

```
//===- lib/ReaderWriter/ELF/Cpu0/Cpu0TargetHandler.cpp ----------------===//
//
//                             The LLVM Linker
//
// This file is distributed under the University of Illinois Open Source
// License. See LICENSE.TXT for details.
//
//===--------------------------------------------------------------------===//

#include "Atoms.h"
#include "Cpu0DynamicLibraryWriter.h"
#include "Cpu0ExecutableWriter.h"
#include "Cpu0LinkingContext.h"
#include "Cpu0TargetHandler.h"

using namespace lld;
using namespace elf;

Cpu0TargetHandler::Cpu0TargetHandler(Cpu0LinkingContext &context)
    : DefaultTargetHandler(context), _context(context),
      _cpu0TargetLayout(new Cpu0TargetLayout<Cpu0ELFType>(context)),
      _cpu0RelocationHandler(
          new Cpu0TargetRelocationHandler(*_cpu0TargetLayout.get(), context,
                                          context)) {}

void Cpu0TargetHandler::registerRelocationNames(Registry &registry) {
  registry.addKindTable(Reference::KindNamespace::ELF,
                        Reference::KindArch::Cpu0, kindStrings);
}

std::unique_ptr<Writer> Cpu0TargetHandler::getWriter() {
  switch (this->_context.getOutputELFType()) {
  case llvm::ELF::ET_EXEC:
    return std::unique_ptr<Writer>(new Cpu0ExecutableWriter<Cpu0ELFType>(
        _context, *_cpu0TargetLayout.get()));
  case llvm::ELF::ET_DYN:
    return std::unique_ptr<Writer>(
        new Cpu0DynamicLibraryWriter<Cpu0ELFType>(
            _context, *_cpu0TargetLayout.get()));
  case llvm::ELF::ET_REL:
    llvm_unreachable("TODO: support -r mode");
  default:
    llvm_unreachable("unsupported output type");
  }
}

#define ELF_RELOC(name, value) LLD_KIND_STRING_ENTRY(name),

const Registry::KindStrings Cpu0TargetHandler::kindStrings[] = {
#include "llvm/Support/ELFRelocs/Cpu0.def"
  LLD_KIND_STRING_ENTRY(LLD_R_CPU0_GOTRELINDEX),
  LLD_KIND_STRING_END
};
```

```
#undef ELF_RELOC
```

exlbt/lld/Cpu0el/CMakeLists.txt

```
add_lld_library(lldCpu0elELFTarget
  Cpu0LinkingContext.cpp
  Cpu0TargetHandler.cpp
  Cpu0RelocationHandler.cpp
  Cpu0RelocationPass.cpp
  )

target_link_libraries(lldCpu0elELFTarget ${cmake_2_8_12_INTERFACE}
  lldCore
  )
```

exlbt/lld/Cpu0el/Cpu0DynamicLibraryWriter.h

```
//===- lib/ReaderWriter/ELF/Cpu0/Cpu0DynamicLibraryWriter.h ---------------===//
//
//                             The LLVM Linker
//
// This file is distributed under the University of Illinois Open Source
// License. See LICENSE.TXT for details.
//
//===----------------------------------------------------------------------===//
#ifndef CPU0EL_DYNAMIC_LIBRARY_WRITER_H
#define CPU0EL_DYNAMIC_LIBRARY_WRITER_H

#include "DynamicLibraryWriter.h"
#include "Cpu0LinkingContext.h"

namespace lld {
namespace elf {

template <class ELFT>
class Cpu0DynamicLibraryWriter : public DynamicLibraryWriter<ELFT> {
public:
  Cpu0DynamicLibraryWriter(Cpu0elLinkingContext &context,
                           Cpu0elTargetLayout<ELFT> &layout);

protected:
  // Add any runtime files and their atoms to the output
  virtual bool createImplicitFiles(std::vector<std::unique_ptr<File>> &);

  virtual void finalizeDefaultAtomValues() {
    return DynamicLibraryWriter<ELFT>::finalizeDefaultAtomValues();
  }

  virtual void addDefaultAtoms() {
    return DynamicLibraryWriter<ELFT>::addDefaultAtoms();
  }

private:
  class GOTFile : public SimpleFile {
```

```
  public:
    GOTFile(const ELFLinkingContext &eti) : SimpleFile("GOTFile") {}
    llvm::BumpPtrAllocator _alloc;
  };

  std::unique_ptr<GOTFile> _gotFile;
  Cpu0elLinkingContext &_context;
  Cpu0elTargetLayout<ELFT> &_cpu0Layout;
};

template <class ELFT>
Cpu0DynamicLibraryWriter<ELFT>::Cpu0DynamicLibraryWriter(
    Cpu0elLinkingContext &context, Cpu0elTargetLayout<ELFT> &layout)
    : DynamicLibraryWriter<ELFT>(context, layout),
      _gotFile(new GOTFile(context)), _context(context), _cpu0Layout(layout) {
}

template <class ELFT>
bool Cpu0DynamicLibraryWriter<ELFT>::createImplicitFiles(
    std::vector<std::unique_ptr<File>> &result) {
  DynamicLibraryWriter<ELFT>::createImplicitFiles(result);
  _gotFile->addAtom(*new (_gotFile->_alloc) GLOBAL_OFFSET_TABLEAtom(*_gotFile));
  _gotFile->addAtom(*new (_gotFile->_alloc) DYNAMICAtom(*_gotFile));
  result.push_back(std::move(_gotFile));
  return true;
}

} // namespace elf
} // namespace lld

#endif
```

exlbt/lld/Cpu0el/Cpu0ExecutableWriter.h

```
//===- lib/ReaderWriter/ELF/Cpu0/Cpu0ExecutableWriter.h -------------------===//
//
//                             The LLVM Linker
//
// This file is distributed under the University of Illinois Open Source
// License. See LICENSE.TXT for details.
//
//===----------------------------------------------------------------------===//
#ifndef CPU0EL_EXECUTABLE_WRITER_H
#define CPU0EL_EXECUTABLE_WRITER_H

#include "ExecutableWriter.h"
#include "Cpu0LinkingContext.h"

namespace lld {
namespace elf {

template <class ELFT>
class Cpu0ExecutableWriter : public ExecutableWriter<ELFT> {
public:
  Cpu0ExecutableWriter(Cpu0elLinkingContext &context,
                       Cpu0elTargetLayout<ELFT> &layout);
```

```
protected:
  // Add any runtime files and their atoms to the output
  virtual bool createImplicitFiles(std::vector<std::unique_ptr<File>> &);

  virtual void finalizeDefaultAtomValues() {
    return ExecutableWriter<ELFT>::finalizeDefaultAtomValues();
  }

  virtual void addDefaultAtoms() {
    return ExecutableWriter<ELFT>::addDefaultAtoms();
  }

private:
  class GOTFile : public SimpleFile {
  public:
    GOTFile(const ELFLinkingContext &eti) : SimpleFile("GOTFile") {}
    llvm::BumpPtrAllocator _alloc;
  };

  std::unique_ptr<GOTFile> _gotFile;
  Cpu0elLinkingContext &_context;
  Cpu0elTargetLayout<ELFT> &_cpu0Layout;
};

template <class ELFT>
Cpu0ExecutableWriter<ELFT>::Cpu0ExecutableWriter(
    Cpu0elLinkingContext &context, Cpu0elTargetLayout<ELFT> &layout)
    : ExecutableWriter<ELFT>(context, layout), _gotFile(new GOTFile(context)),
      _context(context), _cpu0Layout(layout) {}

template <class ELFT>
bool Cpu0ExecutableWriter<ELFT>::createImplicitFiles(
    std::vector<std::unique_ptr<File>> &result) {
  ExecutableWriter<ELFT>::createImplicitFiles(result);
  _gotFile->addAtom(*new (_gotFile->_alloc) GLOBAL_OFFSET_TABLEAtom(*_gotFile));
  if (_context.isDynamic())
    _gotFile->addAtom(*new (_gotFile->_alloc) DYNAMICAtom(*_gotFile));
  result.push_back(std::move(_gotFile));
  return true;
}

} // namespace elf
} // namespace lld

#endif
```

exlbt/lld/Cpu0el/Cpu0LinkingContext.h

```
//===- lib/ReaderWriter/ELF/Cpu0/Cpu0LinkingContext.h ------------------===//
//
//                             The LLVM Linker
//
// This file is distributed under the University of Illinois Open Source
// License. See LICENSE.TXT for details.
//
//===--------------------------------------------------------------------===//
```

```
#ifndef LLD_READER_WRITER_ELF_CPU0EL_CPU0EL_LINKING_CONTEXT_H
#define LLD_READER_WRITER_ELF_CPU0EL_CPU0EL_LINKING_CONTEXT_H

#include "Cpu0TargetHandler.h"

#include "lld/ReaderWriter/ELFLinkingContext.h"

#include "llvm/Object/ELF.h"
#include "llvm/Support/ELF.h"

namespace lld {
namespace elf {

/// \brief Cpu0 internal references.
enum {
  /// \brief The 32 bit index of the relocation in the got this reference refers
  /// to.
  LLD_R_CPU0EL_GOTRELINDEX = 1025,
};

class Cpu0elLinkingContext final : public ELFLinkingContext {
public:
  Cpu0elLinkingContext(llvm::Triple triple)
      : ELFLinkingContext(triple, std::unique_ptr<TargetHandlerBase>(
                                      new Cpu0elTargetHandler(*this))) {}

//  bool isLittleEndian() const override { return false; }

  void addPasses(PassManager &) override;

  uint64_t getBaseAddress() const override {
    if (_baseAddress == 0)
      return 0x000000;
    return _baseAddress;
  }

  bool isDynamicRelocation(const DefinedAtom &,
                           const Reference &r) const override {
    if (r.kindNamespace() != Reference::KindNamespace::ELF)
      return false;
    assert(r.kindArch() == Reference::KindArch::Cpu0);
    switch (r.kindValue()) {
    case llvm::ELF::R_CPU0_GLOB_DAT:
      return true;
    default:
      return false;
    }
  }

  virtual bool isPLTRelocation(const DefinedAtom &,
                               const Reference &r) const override {
    if (r.kindNamespace() != Reference::KindNamespace::ELF)
      return false;
    assert(r.kindArch() == Reference::KindArch::Cpu0);
    switch (r.kindValue()) {
    case llvm::ELF::R_CPU0_JUMP_SLOT:
    case llvm::ELF::R_CPU0_RELGOT:
      return true;
```

```
    default:
      return false;
    }
  }

  /// \brief Cpu0 has two relative relocations
  /// a) for supporting relative relocs - R_CPU0_RELGOT
  bool isRelativeReloc(const Reference &r) const override {
    if (r.kindNamespace() != Reference::KindNamespace::ELF)
      return false;
    assert(r.kindArch() == Reference::KindArch::Cpu0);
    switch (r.kindValue()) {
    case llvm::ELF::R_CPU0_RELGOT:
      return true;
    default:
      return false;
    }
  }

  bool isStaticExecutable() const { return _isStaticExecutable; }
};
} // end namespace elf
} // end namespace lld

#endif
```

exlbt/lld/Cpu0el/Cpu0LinkingContext.cpp

```
//===- lib/ReaderWriter/ELF/Cpu0/Cpu0LinkingContext.cpp ---------------===//
//
//                             The LLVM Linker
//
// This file is distributed under the University of Illinois Open Source
// License. See LICENSE.TXT for details.
//
//===--------------------------------------------------------------------===//

#include "Cpu0LinkingContext.h"
#include "Cpu0RelocationPass.h"

using namespace lld;

void elf::Cpu0elLinkingContext::addPasses(PassManager &pm) {
  auto pass = createCpu0RelocationPass(*this);
  if (pass)
    pm.add(std::move(pass));
  ELFLinkingContext::addPasses(pm);
}
```

exlbt/lld/Cpu0el/Cpu0RelocationHandler.h

```
//===- lib/ReaderWriter/ELF/Cpu0/Cpu0RelocationHandler.h --------------===//
//
//                             The LLVM Linker
//
```

```
// This file is distributed under the University of Illinois Open Source
// License. See LICENSE.TXT for details.
//
//===----------------------------------------------------------------------===//

#ifndef CPU0EL_RELOCATION_HANDLER_H
#define CPU0EL_RELOCATION_HANDLER_H

#include "Cpu0TargetHandler.h"

namespace lld {
namespace elf {
typedef llvm::object::ELFType<llvm::support::little, 2, false> Cpu0elELFType;
class Cpu0elLinkingContext;

template <class ELFT> class Cpu0elTargetLayout;

class Cpu0elTargetRelocationHandler final
    : public TargetRelocationHandler<Cpu0elELFType> {
public:
  Cpu0elTargetRelocationHandler(Cpu0elTargetLayout<Cpu0elELFType> &layout,
                                Cpu0elLinkingContext &context,
                                ELFLinkingContext &targetInfo)
      : TargetRelocationHandler<Cpu0elELFType>(targetInfo),
        _tlsSize(0), _cpu0Layout(layout),
        _context(context) {}

  std::error_code applyRelocation(ELFWriter &, llvm::FileOutputBuffer &,
                                  const lld::AtomLayout &,
                                  const Reference &) const override;

private:
  // Cached size of the TLS segment.
  mutable uint64_t _tlsSize;
  Cpu0elTargetLayout<Cpu0elELFType> &_cpu0Layout;
  Cpu0elLinkingContext &_context;
};

} // end namespace elf
} // end namespace lld

#endif // CPU0EL_RELOCATION_HANDLER_H
```

exlbt/lld/Cpu0el/Cpu0RelocationHandler.cpp

```
//===- lib/ReaderWriter/ELF/Cpu0/Cpu0RelocationHandler.cpp ----------===//
//
//                             The LLVM Linker
//
// This file is distributed under the University of Illinois Open Source
// License. See LICENSE.TXT for details.
//
//===----------------------------------------------------------------------===//

#include "Cpu0TargetHandler.h"
#include "Cpu0LinkingContext.h"
```

```
#include "llvm/Object/ObjectFile.h"
#include "llvm/Support/raw_ostream.h"

using namespace lld;
using namespace elf;
using namespace llvm;
using namespace object;

static bool error(std::error_code ec) {
  if (!ec) return false;

  outs() << "Cpu0RelocationHandler.cpp : error reading file: "
         << ec.message() << ".\n";
  outs().flush();
  return true;
}

namespace {
/// \brief R_CPU0_HI16 - word64: (S + A) >> 16
void relocHI16(uint8_t *location, uint64_t P, uint64_t S, int64_t A) {
 // Don't know why A, ref.addend(), = 9
  uint32_t result = (uint32_t)(S >> 16);
  *reinterpret_cast<llvm::support::ulittle32_t *>(location) =
      result |
      (uint32_t) * reinterpret_cast<llvm::support::ulittle32_t *>(location);
}

void relocLO16(uint8_t *location, uint64_t P, uint64_t S, uint64_t A) {
 // Don't know why A, ref.addend(), = 9
  uint32_t result = (uint32_t)(S & 0x0000ffff);
  *reinterpret_cast<llvm::support::ulittle32_t *>(location) =
      result |
      (uint32_t) * reinterpret_cast<llvm::support::ulittle32_t *>(location);
}

/// \brief R_CPU0_GOT16 - word32: S
void relocGOT16(uint8_t *location, uint64_t P, uint64_t S, int64_t A) {
  uint32_t result = (uint32_t)(S);
  *reinterpret_cast<llvm::support::ulittle32_t *>(location) =
      result |
      (uint32_t) * reinterpret_cast<llvm::support::ulittle32_t *>(location);
}

/// \brief R_CPU0_PC24 - word32: S + A - P
void relocPC24(uint8_t *location, uint64_t P, uint64_t S, int64_t A) {
  uint32_t result = (uint32_t)(S  - P);

  uint32_t machinecode = (uint32_t) *
                         reinterpret_cast<llvm::support::ulittle32_t *>(location);
  uint32_t opcode = (machinecode & 0xff000000);
  uint32_t offset = (machinecode & 0x00ffffff);
  *reinterpret_cast<llvm::support::ulittle32_t *>(location) =
      (((result + offset) & 0x00ffffff) | opcode);
}

/// \brief R_CPU0_32 - word32:  S
void reloc32(uint8_t *location, uint64_t P, uint64_t S, int64_t A) {
  int32_t result = (uint32_t)(S);
```

```
  *reinterpret_cast<llvm::support::ulittle32_t *>(location) =
      result |
      (uint32_t) * reinterpret_cast<llvm::support::ubig32_t *>(location);
  // TODO: Make sure that the result zero extends to the 64bit value.
}
} // end anon namespace

#ifdef DLINKER
class Cpu0elSoPlt {
private:
  uint32_t funAddr[100];
  int funAddrSize = 0;
public:
  Cpu0elTargetLayout<Cpu0elELFType> *_cpu0Layout;
  void createFunAddr(Cpu0elTargetLayout<Cpu0elELFType> *cpu0Layout,
                     llvm::FileOutputBuffer &buf);
  // Return function index, 1: 1st function appear on section .text of .so.
  //   2: 2nd function ...
  // For example: 3 functions _Z2laii, _Z3fooii and _Z3barv. 1: is _Z2laii
  //   2 is _Z3fooii, 3: is _Z3barv.
  int getDynFunIndexByTargetAddr(uint64_t fAddr);
};

void Cpu0elSoPlt::createFunAddr(Cpu0elTargetLayout<Cpu0elELFType> *cpu0Layout,
                                llvm::FileOutputBuffer &buf) {
  auto dynsymSection = cpu0Layout->
                       findOutputSection(".dynsym");
  uint64_t dynsymFileOffset, dynsymSize;
  if (dynsymSection) {
    dynsymFileOffset = dynsymSection->fileOffset();
    dynsymSize = dynsymSection->memSize();
    uint8_t *atomContent = buf.getBufferStart() + dynsymFileOffset;
    for (uint64_t i = 4; i < dynsymSize; i += 16) {
      funAddr[funAddrSize] =
        *reinterpret_cast<llvm::support::ubig32_t*>((uint32_t*)
        (atomContent + i));
      funAddrSize++;
    }
  }
}

int Cpu0elSoPlt::getDynFunIndexByTargetAddr(uint64_t fAddr) {
  for (int i = 0; i < funAddrSize; i++) {
    // Below statement fix the issue that both __tls_get_addr and first
    // function has the same file offset 0 issue.
    if (i < (funAddrSize-1) && funAddr[i] == funAddr[i+1])
      continue;

    if (fAddr == funAddr[i]) {
      return i;
    }
  }
  return -1;
}

Cpu0elSoPlt cpu0elSoPlt;
#endif // DLINKER
```

```
std::error_code Cpu0elTargetRelocationHandler::applyRelocation(
    ELFWriter &writer, llvm::FileOutputBuffer &buf, const lld::AtomLayout &atom,
    const Reference &ref) const {
#ifdef DLINKER
  static bool firstTime = true;
  std::string soName("libfoobar.cpu0.so");
  int idx = 0;
  if (firstTime) {
    if (this->_context.getOutputELFType() == llvm::ELF::ET_DYN) {
      cpu0elSoPlt.createFunAddr(&(this->_cpu0Layout), buf);
    }
    else if (this->_context.getOutputELFType() == llvm::ELF::ET_EXEC &&
             !this->_context.isStaticExecutable()) {
      cpu0elSoPlt.createFunAddr(&(this->_cpu0Layout), buf);
    }
    firstTime = false;
  }
#endif // DLINKER
  uint8_t *atomContent = buf.getBufferStart() + atom._fileOffset;
  uint8_t *location = atomContent + ref.offsetInAtom();
  uint64_t targetVAddress = writer.addressOfAtom(ref.target());
  uint64_t relocVAddress = atom._virtualAddr + ref.offsetInAtom();
#if 1 // For case R_CPU0_GOT16:
//  auto gotAtomIter = _context.getTargetHandler<Cpu0elELFType>().targetLayout().
//                     findAbsoluteAtom("_GLOBAL_OFFSET_TABLE_");
//  uint64_t globalOffsetTableAddress = writer.addressOfAtom(*gotAtomIter);
// .got.plt start from _GLOBAL_OFFSET_TABLE_
  auto gotpltSection = _cpu0Layout.findOutputSection(".got.plt");
  uint64_t gotPltFileOffset;
  if (gotpltSection)
    gotPltFileOffset = gotpltSection->fileOffset();
  else
    gotPltFileOffset = 0;
#endif

  if (ref.kindNamespace() != Reference::KindNamespace::ELF)
    return std::error_code();
  assert(ref.kindArch() == Reference::KindArch::Cpu0);
  switch (ref.kindValue()) {
  case R_CPU0_NONE:
    break;

  case R_CPU0_HI16:
    relocHI16(location, relocVAddress, targetVAddress, ref.addend());
    break;
  case R_CPU0_LO16:
    relocLO16(location, relocVAddress, targetVAddress, ref.addend());
    break;
#if 0 // Not support yet
  case R_CPU0_GOT16:
#if 1
    idx = cpu0elSoPlt.getDynFunIndexByTargetAddr(targetVAddress);
    relocGOT16(location, relocVAddress, idx, ref.addend());
#else
    relocGOT16(location, relocVAddress, (targetVAddress - gotPltFileOffset),
               ref.addend());
#endif
    break;
```

```
#endif
  case R_CPU0_PC24:
    relocPC24(location, relocVAddress, targetVAddress, ref.addend());
    break;
#ifdef DLINKER
  case R_CPU0_CALL16:
  // offset at _GLOBAL_OFFSET_TABLE_ and $gp point to _GLOBAL_OFFSET_TABLE_.
    idx = cpu0elSoPlt.getDynFunIndexByTargetAddr(targetVAddress);
    reloc32(location, relocVAddress, idx*0x04+16, ref.addend());
    break;
#endif // DLINKER
  case R_CPU0_32:
    reloc32(location, relocVAddress, targetVAddress, ref.addend());
    break;

  // Runtime only relocations. Ignore here.
  case R_CPU0_JUMP_SLOT:
  case R_CPU0_GLOB_DAT:
    break;
  default:
    unhandledReferenceType(*atom._atom, ref);
  }

  return std::error_code();
}
```

exlbt/lld/Cpu0el/Cpu0RelocationPass.h

```
//===- lib/ReaderWriter/ELF/Cpu0/Cpu0RelocationPass.h ------------------===//
//
//                             The LLVM Linker
//
// This file is distributed under the University of Illinois Open Source
// License. See LICENSE.TXT for details.
//
//===--------------------------------------------------------------------===//
///
/// \file
/// \brief Declares the relocation processing pass for Cpu0. This includes
///   GOT and PLT entries, TLS, COPY, and ifunc.
///
//===--------------------------------------------------------------------===//

#ifndef LLD_READER_WRITER_ELF_CPU0EL_CPU0EL_RELOCATION_PASS_H
#define LLD_READER_WRITER_ELF_CPU0EL_CPU0EL_RELOCATION_PASS_H

#include <memory>

namespace lld {
class Pass;
namespace elf {
class Cpu0elLinkingContext;

/// \brief Create Cpu0 relocation pass for the given linking context.
std::unique_ptr<Pass>
createCpu0RelocationPass(const Cpu0elLinkingContext &);
```

```
}
}

#endif
```

exlbt/lld/Cpu0el/Cpu0RelocationPass.cpp

```
//===- lib/ReaderWriter/ELF/Cpu0/Cpu0RelocationPass.cpp ---------------===//
//
//                             The LLVM Linker
//
// This file is distributed under the University of Illinois Open Source
// License. See LICENSE.TXT for details.
//
//===---------------------------------------------------------------------===//
///
/// \file
/// \brief Defines the relocation processing pass for Cpu0. This includes
///   GOT and PLT entries, TLS, COPY, and ifunc.
///
/// This is based on section 4.4.1 of the AMD64 ABI (no stable URL as of Oct,
/// 2013).
///
/// This also includes aditional behaivor that gnu-ld and gold implement but
/// which is not specified anywhere.
///
//===---------------------------------------------------------------------===//

#include "Atoms.h"
#include "Cpu0RelocationPass.h"
#include "Cpu0LinkingContext.h"

#include "lld/Core/Simple.h"

#include "llvm/ADT/DenseMap.h"


using namespace lld;
using namespace lld::elf;
using namespace llvm::ELF;

namespace {
// .plt value (entry 0)
const uint8_t cpu0BootAtomContent[16] = {
  0xfc, 0xff, 0xff, 0x36, // jmp start
  0x04, 0x00, 0x00, 0x36, // jmp 4
  0xfc, 0xff, 0xff, 0x36, // jmp ISR
  0xfc, 0xff, 0xff, 0x36 // jmp -4
};

#ifdef DLINKER
// .got values
const uint8_t cpu0GotAtomContent[16] = { 0 };

// .plt value (entry 0)
const uint8_t cpu0Plt0AtomContent[16] = {
  0x04, 0x00, 0xeb, 0x02, // st $lr, $zero, reloc-index ($gp)
```

```
  0x08, 0x00, 0xcb, 0x02, // st $fp, $zero, reloc-index ($gp)
  0x0c, 0x00, 0xdb, 0x02, // st $sp, $zero, reloc-index ($gp)
  0xfc, 0xff, 0xff, 0x36  // jmp dynamic_linker
};

// .plt values (other entries)
const uint8_t cpu0PltAtomContent[16] = {
  0x10, 0x00, 0x6b, 0x01, // ld $t9, 0x10($gp) (0x10($gp) point to plt0
  0x00, 0x00, 0x60, 0x3c, // ret $t9 // jump to Cpu0.Stub
  0x00, 0x00, 0x00, 0x00, // nop
  0x00, 0x00, 0x00, 0x00  // nop
};
#endif // DLINKER

/// boot record
class Cpu0BootAtom : public PLT0Atom {
public:
  Cpu0BootAtom(const File &f) : PLT0Atom(f) {
#ifndef NDEBUG
    _name = ".PLT0";
#endif
  }
  virtual ArrayRef<uint8_t> rawContent() const {
    return ArrayRef<uint8_t>(cpu0BootAtomContent, 16);
  }
};

#ifdef DLINKER
/// \brief Atoms that are used by Cpu0 dynamic linking
class Cpu0GOTAtom : public GOTAtom {
public:
  Cpu0GOTAtom(const File &f, StringRef secName) : GOTAtom(f, secName) {}

  ArrayRef<uint8_t> rawContent() const override {
    return ArrayRef<uint8_t>(cpu0GotAtomContent, 16);
  }
};

class Cpu0PLT0Atom : public PLT0Atom {
public:
  Cpu0PLT0Atom(const File &f) : PLT0Atom(f) {
#ifndef NDEBUG
    _name = ".PLT0";
#endif
  }
  ArrayRef<uint8_t> rawContent() const override {
    return ArrayRef<uint8_t>(cpu0Plt0AtomContent, 16);
  }
};

class Cpu0PLTAtom : public PLTAtom {
public:
  Cpu0PLTAtom(const File &f, StringRef secName) : PLTAtom(f, secName) {}

  ArrayRef<uint8_t> rawContent() const override {
    return ArrayRef<uint8_t>(cpu0PltAtomContent, 16);
  }
};
```

```
#endif // DLINKER

class ELFPassFile : public SimpleFile {
public:
  ELFPassFile(const ELFLinkingContext &eti) : SimpleFile("ELFPassFile") {
    setOrdinal(eti.getNextOrdinalAndIncrement());
  }

  llvm::BumpPtrAllocator _alloc;
};

/// \brief CRTP base for handling relocations.
template <class Derived> class RelocationPass : public Pass {
  /// \brief Handle a specific reference.
  void handleReference(const DefinedAtom &atom, const Reference &ref) {
    if (ref.kindNamespace() != Reference::KindNamespace::ELF)
      return;
    assert(ref.kindArch() == Reference::KindArch::Cpu0);
    switch (ref.kindValue()) {
    case R_CPU0_CALL16:
      static_cast<Derived *>(this)->handlePLT32(ref);
      break;

    case R_CPU0_PC24:
      static_cast<Derived *>(this)->handlePlain(ref);
      break;
    }
  }

protected:
#ifdef DLINKER
  /// \brief get the PLT entry for a given IFUNC Atom.
  ///
  /// If the entry does not exist. Both the GOT and PLT entry is created.
  const PLTAtom *getIFUNCPLTEntry(const DefinedAtom *da) {
    auto plt = _pltMap.find(da);
    if (plt != _pltMap.end())
      return plt->second;
    auto ga = new (_file._alloc) Cpu0GOTAtom(_file, ".got.plt");
    ga->addReferenceELF_Cpu0(R_CPU0_RELGOT, 0, da, 0);
    auto pa = new (_file._alloc) Cpu0PLTAtom(_file, ".plt");
    pa->addReferenceELF_Cpu0(R_CPU0_PC24, 2, ga, -4);
#ifndef NDEBUG
    ga->_name = "__got_ifunc_";
    ga->_name += da->name();
    pa->_name = "__plt_ifunc_";
    pa->_name += da->name();
#endif
    _gotMap[da] = ga;
    _pltMap[da] = pa;
    _gotVector.push_back(ga);
    _pltVector.push_back(pa);
    return pa;
  }
#endif // DLINKER

  /// \brief Redirect the call to the PLT stub for the target IFUNC.
  ///
```

```
  /// This create a PLT and GOT entry for the IFUNC if one does not exist. The
  /// GOT entry and a IRELATIVE relocation to the original target resolver.
  std::error_code handleIFUNC(const Reference &ref) {
    auto target = dyn_cast_or_null<const DefinedAtom>(ref.target());
#ifdef DLINKER
    if (target && target->contentType() == DefinedAtom::typeResolver)
      const_cast<Reference &>(ref).setTarget(getIFUNCPLTEntry(target));
#endif // DLINKER
    return std::error_code();
  }

  /// \brief Create a GOT entry for the TP offset of a TLS atom.
  const GOTAtom *getGOTTPOFF(const Atom *atom) {
    auto got = _gotMap.find(atom);
    if (got == _gotMap.end()) {
      auto g = new (_file._alloc) Cpu0GOTAtom(_file, ".got");
      g->addReferenceELF_Cpu0(R_CPU0_TLS_TPREL32, 0, atom, 0);
#ifndef NDEBUG
      g->_name = "__got_tls_";
      g->_name += atom->name();
#endif
      _gotMap[atom] = g;
      _gotVector.push_back(g);
      return g;
    }
    return got->second;
  }

  /// \brief Create a GOT entry containing 0.
  const GOTAtom *getNullGOT() {
    if (!_null) {
      _null = new (_file._alloc) Cpu0GOTAtom(_file, ".got.plt");
#ifndef NDEBUG
      _null->_name = "__got_null";
#endif
    }
    return _null;
  }

  const GOTAtom *getGOT(const DefinedAtom *da) {
    auto got = _gotMap.find(da);
    if (got == _gotMap.end()) {
      auto g = new (_file._alloc) Cpu0GOTAtom(_file, ".got");
      g->addReferenceELF_Cpu0(R_CPU0_32, 0, da, 0);
#ifndef NDEBUG
      g->_name = "__got_";
      g->_name += da->name();
#endif
      _gotMap[da] = g;
      _gotVector.push_back(g);
      return g;
    }
    return got->second;
  }

public:
  RelocationPass(const ELFLinkingContext &ctx)
      : _file(ctx), _ctx(ctx), _null(nullptr), _PLT0(nullptr), _got0(nullptr),
```

```
        _boot(new Cpu0BootAtom(_file)) {}

  /// \brief Do the pass.
  ///
  /// The goal here is to first process each reference individually. Each call
  /// to handleReference may modify the reference itself and/or create new
  /// atoms which must be stored in one of the maps below.
  ///
  /// After all references are handled, the atoms created during that are all
  /// added to mf.
  void perform(std::unique_ptr<MutableFile> &mf) override {
    ScopedTask task(getDefaultDomain(), "Cpu0 GOT/PLT Pass");
    // Process all references.
    for (const auto &atom : mf->defined())
      for (const auto &ref : *atom)
        handleReference(*atom, *ref);

    // Add all created atoms to the link.
    uint64_t ordinal = 0;
    if (_ctx.getOutputELFType() == llvm::ELF::ET_EXEC) {
      MutableFile::DefinedAtomRange atomRange = mf->definedAtoms();
      auto it = atomRange.begin();
      bool find = false;
      for (it = atomRange.begin(); it < atomRange.end(); it++) {
        if ((*it)->name() == "start") {
          find = true;
          break;
        }
      }
      assert(find && "not found start\n");
      _boot->addReferenceELF_Cpu0(R_CPU0_PC24, 0, *it, -3);
      find = false;
      for (it = atomRange.begin(); it < atomRange.end(); it++) {
        if ((*it)->name() == "ISR") {
          find = true;
          break;
        }
      }
      assert(find && "not found ISR\n");
      _boot->addReferenceELF_Cpu0(R_CPU0_PC24, 8, *it, -3);
      _boot->setOrdinal(ordinal++);
      mf->addAtom(*_boot);
    }
#ifdef DLINKER
    if (_PLT0) {
      MutableFile::DefinedAtomRange atomRange = mf->definedAtoms();
      auto it = atomRange.begin();
      bool find = false;
      for (it = atomRange.begin(); it < atomRange.end(); it++) {
        if ((*it)->name() == "_Z14dynamic_linkerv") {
          find = true;
          break;
        }
      }
      assert(find && "Cannot find _Z14dynamic_linkerv()");
      _PLT0->addReferenceELF_Cpu0(R_CPU0_PC24, 12, *it, -3);
      _PLT0->setOrdinal(ordinal++);
      mf->addAtom(*_PLT0);
```

```
    }
    for (auto &plt : _pltVector) {
      plt->setOrdinal(ordinal++);
      mf->addAtom(*plt);
    }
    if (_null) {
      _null->setOrdinal(ordinal++);
      mf->addAtom(*_null);
    }
    if (_PLT0) {
      _got0->setOrdinal(ordinal++);
      mf->addAtom(*_got0);
    }
    for (auto &got : _gotVector) {
      got->setOrdinal(ordinal++);
      mf->addAtom(*got);
    }
    for (auto obj : _objectVector) {
      obj->setOrdinal(ordinal++);
      mf->addAtom(*obj);
    }
#endif // DLINKER
  }

protected:
  /// \brief Owner of all the Atoms created by this pass.
  ELFPassFile _file;
  const ELFLinkingContext &_ctx;

  /// \brief Map Atoms to their GOT entries.
  llvm::DenseMap<const Atom *, GOTAtom *> _gotMap;

  /// \brief Map Atoms to their PLT entries.
  llvm::DenseMap<const Atom *, PLTAtom *> _pltMap;

  /// \brief Map Atoms to their Object entries.
  llvm::DenseMap<const Atom *, ObjectAtom *> _objectMap;

  /// \brief the list of GOT/PLT atoms
  std::vector<GOTAtom *> _gotVector;
  std::vector<PLTAtom *> _pltVector;
  std::vector<ObjectAtom *> _objectVector;
  PLT0Atom *_boot;

  /// \brief GOT entry that is always 0. Used for undefined weaks.
  GOTAtom *_null;

  /// \brief The got and plt entries for .PLT0. This is used to call into the
  /// dynamic linker for symbol resolution.
  /// @{
  PLT0Atom *_PLT0;
  GOTAtom *_got0;
  /// @}
};

/// This implements the static relocation model. Meaning GOT and PLT entries are
/// not created for references that can be directly resolved. These are
/// converted to a direct relocation. For entries that do require a GOT or PLT
```

```
/// entry, that entry is statically bound.
///
/// TLS always assumes module 1 and attempts to remove indirection.
class StaticRelocationPass final
    : public RelocationPass<StaticRelocationPass> {
public:
  StaticRelocationPass(const elf::Cpu0elLinkingContext &ctx)
      : RelocationPass(ctx) {}

  std::error_code handlePlain(const Reference &ref) { return handleIFUNC(ref); }

  std::error_code handlePLT32(const Reference &ref) {
    // __tls_get_addr is handled elsewhere.
    if (ref.target() && ref.target()->name() == "__tls_get_addr") {
      const_cast<Reference &>(ref).setKindValue(R_CPU0_NONE);
      return std::error_code();
    }
    // Static code doesn't need PLTs.
    const_cast<Reference &>(ref).setKindValue(R_CPU0_PC24);
    // Handle IFUNC.
    if (const DefinedAtom *da =
            dyn_cast_or_null<const DefinedAtom>(ref.target()))
      if (da->contentType() == DefinedAtom::typeResolver)
        return handleIFUNC(ref);
    return std::error_code();
  }

  std::error_code handleGOT(const Reference &ref) {
    if (isa<UndefinedAtom>(ref.target()))
      const_cast<Reference &>(ref).setTarget(getNullGOT());
    else if (const DefinedAtom *da = dyn_cast<const DefinedAtom>(ref.target()))
      const_cast<Reference &>(ref).setTarget(getGOT(da));
    return std::error_code();
  }
};

#ifdef DLINKER
class DynamicRelocationPass final
    : public RelocationPass<DynamicRelocationPass> {
public:
  DynamicRelocationPass(const elf::Cpu0elLinkingContext &ctx)
      : RelocationPass(ctx) {}

  const PLT0Atom *getPLT0() {
    if (_PLT0)
      return _PLT0;
    // Fill in the null entry.
    getNullGOT();
    _PLT0 = new (_file._alloc) Cpu0PLT0Atom(_file);
    _got0 = new (_file._alloc) Cpu0GOTAtom(_file, ".got.plt");
#ifndef NDEBUG
    _got0->_name = "__got0";
#endif
    return _PLT0;
  }

  const PLTAtom *getPLTEntry(const Atom *a) {
    auto plt = _pltMap.find(a);
```

```
    if (plt != _pltMap.end())
      return plt->second;
    auto ga = new (_file._alloc) Cpu0GOTAtom(_file, ".got.plt");
    ga->addReferenceELF_Cpu0(R_CPU0_JUMP_SLOT, 0, a, 0);
    auto pa = new (_file._alloc) Cpu0PLTAtom(_file, ".plt");
    getPLT0();  // add _PLT0 and _got0

    // Set the starting address of the got entry to the second instruction in
    // the plt entry.
    ga->addReferenceELF_Cpu0(R_CPU0_32, 0, pa, 4);
#ifndef NDEBUG
    ga->_name = "__got_";
    ga->_name += a->name();
    pa->_name = "__plt_";
    pa->_name += a->name();
#endif
    _gotMap[a] = ga;
    _pltMap[a] = pa;
    _gotVector.push_back(ga);
    _pltVector.push_back(pa);
    return pa;
  }

#if 0 // Not support at this point
  const ObjectAtom *getObjectEntry(const SharedLibraryAtom *a) {
    auto obj = _objectMap.find(a);
    if (obj != _objectMap.end())
      return obj->second;

    auto oa = new (_file._alloc) ObjectAtom(_file);
    // This needs to point to the atom that we just created.
    oa->addReferenceELF_Cpu0(R_Cpu0_COPY, 0, oa, 0);

    oa->_name = a->name();
    oa->_size = a->size();

    _objectMap[a] = oa;
    _objectVector.push_back(oa);
    return oa;
  }
#endif

  std::error_code handlePlain(const Reference &ref) {
    if (!ref.target())
      return std::error_code();
    if (auto sla = dyn_cast<SharedLibraryAtom>(ref.target())) {
#if 0 // Not support at this point
      if (sla->type() == SharedLibraryAtom::Type::Data)
        const_cast<Reference &>(ref).setTarget(getObjectEntry(sla));
      else
#endif
      if (sla->type() == SharedLibraryAtom::Type::Code)
        const_cast<Reference &>(ref).setTarget(getPLTEntry(sla));
    } else
      return handleIFUNC(ref);
    return std::error_code();
  }
```

```
  std::error_code handlePLT32(const Reference &ref) {
    // Handle IFUNC.
    if (const DefinedAtom *da =
            dyn_cast_or_null<const DefinedAtom>(ref.target()))
      if (da->contentType() == DefinedAtom::typeResolver)
        return handleIFUNC(ref);
    if (isa<const SharedLibraryAtom>(ref.target())) {
      const_cast<Reference &>(ref).setTarget(getPLTEntry(ref.target()));
      // Turn this into a PC24 to the PLT entry.
    #if 1
      const_cast<Reference &>(ref).setKindValue(R_CPU0_PC24);
    #endif
    }
    return std::error_code();
  }

  const GOTAtom *getSharedGOT(const Atom *a) {
    auto got = _gotMap.find(a);
    if (got == _gotMap.end()) {
      auto g = new (_file._alloc) Cpu0GOTAtom(_file, ".got.dyn");
      g->addReferenceELF_Cpu0(R_CPU0_GLOB_DAT, 0, a, 0);
#ifndef NDEBUG
      g->_name = "__got_";
      g->_name += a->name();
#endif
      _gotMap[a] = g;
      _gotVector.push_back(g);
      return g;
    }
    return got->second;
  }

  std::error_code handleGOT(const Reference &ref) {
    if (const DefinedAtom *da = dyn_cast<const DefinedAtom>(ref.target()))
      const_cast<Reference &>(ref).setTarget(getGOT(da));
    // Handle undefined atoms in the same way as shared lib atoms: to be
    // resolved at run time.
    else if (isa<SharedLibraryAtom>(ref.target()) ||
             isa<UndefinedAtom>(ref.target()))
      const_cast<Reference &>(ref).setTarget(getSharedGOT(ref.target()));
    return std::error_code();
  }
};
#endif // DLINKER
} // end anon namespace

std::unique_ptr<Pass>
lld::elf::createCpu0RelocationPass(const Cpu0elLinkingContext &ctx) {
  switch (ctx.getOutputELFType()) {
  case llvm::ELF::ET_EXEC:
  // when the output file is execution file: e.g. a.out
#ifdef DLINKER
    if (ctx.isDynamic())
    // when the a.out refer to shared object *.so
      return std::unique_ptr<Pass>(new DynamicRelocationPass(ctx));
    else
#endif // DLINKER
      return std::unique_ptr<Pass>(new StaticRelocationPass(ctx));
```

```
#ifdef DLINKER
  case llvm::ELF::ET_DYN:
  // when the output file is shared object: e.g. foobar.so
    return std::unique_ptr<Pass>(new DynamicRelocationPass(ctx));
#endif // DLINKER
  case llvm::ELF::ET_REL:
    return std::unique_ptr<Pass>();
  default:
    llvm_unreachable("Unhandled output file type");
  }
}
```

exlbt/lld/Cpu0el/Cpu0LinkingContext.cpp

```
//===- lib/ReaderWriter/ELF/Cpu0/Cpu0LinkingContext.cpp ----------------===//
//
//                             The LLVM Linker
//
// This file is distributed under the University of Illinois Open Source
// License. See LICENSE.TXT for details.
//
//===---------------------------------------------------------------------===//

#include "Cpu0LinkingContext.h"
#include "Cpu0RelocationPass.h"

using namespace lld;

void elf::Cpu0elLinkingContext::addPasses(PassManager &pm) {
  auto pass = createCpu0RelocationPass(*this);
  if (pass)
    pm.add(std::move(pass));
  ELFLinkingContext::addPasses(pm);
}
```

exlbt/lld/Cpu0el/Cpu0Target.h

```
//===- lib/ReaderWriter/ELF/Cpu0/Cpu0Target.h --------------------------===//
//
//                             The LLVM Linker
//
// This file is distributed under the University of Illinois Open Source
// License. See LICENSE.TXT for details.
//
//===---------------------------------------------------------------------===//

#include "Cpu0LinkingContext.h"
```

exlbt/lld/Cpu0el/Cpu0TargetHandler.h

```
//===- lib/ReaderWriter/ELF/Cpu0/Cpu0TargetHandler.h -------------------===//
//
//                             The LLVM Linker
```

```
//
// This file is distributed under the University of Illinois Open Source
// License. See LICENSE.TXT for details.
//
//===----------------------------------------------------------------------===//

#ifndef LLD_READER_WRITER_ELF_CPU0EL_CPU0EL_TARGET_HANDLER_H
#define LLD_READER_WRITER_ELF_CPU0EL_CPU0EL_TARGET_HANDLER_H

#include "Cpu0ELFFile.h"
#include "Cpu0ELFReader.h"
#include "Cpu0RelocationHandler.h"
#include "DefaultTargetHandler.h"
#include "TargetLayout.h"

#include "lld/Core/Simple.h"

#define DLINKER

namespace lld {
namespace elf {
typedef llvm::object::ELFType<llvm::support::little, 2, false> Cpu0elELFType;
class Cpu0elLinkingContext;

template <class ELFT> class Cpu0elTargetLayout : public TargetLayout<ELFT> {
public:
  Cpu0elTargetLayout(Cpu0elLinkingContext &context)
      : TargetLayout<ELFT>(context) {}
};

class Cpu0elTargetHandler final
    : public DefaultTargetHandler<Cpu0elELFType> {
public:
  Cpu0elTargetHandler(Cpu0elLinkingContext &context);

  Cpu0elTargetLayout<Cpu0elELFType> &getTargetLayout() override {
    return *(_cpu0TargetLayout.get());
  }

  void registerRelocationNames(Registry &registry) override;

  const Cpu0elTargetRelocationHandler &getRelocationHandler() const override {
    return *(_cpu0RelocationHandler.get());
  }

  std::unique_ptr<Reader> getObjReader(bool atomizeStrings) override {
    return std::unique_ptr<Reader>(new Cpu0elELFObjectReader(atomizeStrings));
  }

  std::unique_ptr<Reader> getDSOReader(bool useShlibUndefines) override {
    return std::unique_ptr<Reader>(new Cpu0elELFDSOReader(useShlibUndefines));
  }

  std::unique_ptr<Writer> getWriter() override;

private:
  static const Registry::KindStrings kindStrings[];
  Cpu0elLinkingContext &_context;
```

```
  std::unique_ptr<Cpu0elTargetLayout<Cpu0elELFType>> _cpu0TargetLayout;
  std::unique_ptr<Cpu0elTargetRelocationHandler> _cpu0RelocationHandler;
};

} // end namespace elf
} // end namespace lld

#endif
```

exlbt/lld/Cpu0el/Cpu0TargetHandler.cpp

```
//===- lib/ReaderWriter/ELF/Cpu0/Cpu0TargetHandler.cpp ----------------===//
//
//                             The LLVM Linker
//
// This file is distributed under the University of Illinois Open Source
// License. See LICENSE.TXT for details.
//
//===--------------------------------------------------------------------===//

#include "Atoms.h"
#include "Cpu0DynamicLibraryWriter.h"
#include "Cpu0ExecutableWriter.h"
#include "Cpu0LinkingContext.h"
#include "Cpu0TargetHandler.h"

using namespace lld;
using namespace elf;

Cpu0TargetHandler::Cpu0TargetHandler(Cpu0LinkingContext &context)
    : DefaultTargetHandler(context), _context(context),
      _cpu0TargetLayout(new Cpu0TargetLayout<Cpu0ELFType>(context)),
      _cpu0RelocationHandler(
          new Cpu0TargetRelocationHandler(*_cpu0TargetLayout.get(), context,
                                          context)) {}

void Cpu0TargetHandler::registerRelocationNames(Registry &registry) {
  registry.addKindTable(Reference::KindNamespace::ELF,
                        Reference::KindArch::Cpu0, kindStrings);
}

std::unique_ptr<Writer> Cpu0TargetHandler::getWriter() {
  switch (this->_context.getOutputELFType()) {
  case llvm::ELF::ET_EXEC:
    return std::unique_ptr<Writer>(new Cpu0ExecutableWriter<Cpu0ELFType>(
        _context, *_cpu0TargetLayout.get()));
  case llvm::ELF::ET_DYN:
    return std::unique_ptr<Writer>(
        new Cpu0DynamicLibraryWriter<Cpu0ELFType>(
            _context, *_cpu0TargetLayout.get()));
  case llvm::ELF::ET_REL:
    llvm_unreachable("TODO: support -r mode");
  default:
    llvm_unreachable("unsupported output type");
  }
}
```

```
#define ELF_RELOC(name, value) LLD_KIND_STRING_ENTRY(name),

const Registry::KindStrings Cpu0TargetHandler::kindStrings[] = {
#include "llvm/Support/ELFRelocs/Cpu0.def"
  LLD_KIND_STRING_ENTRY(LLD_R_CPU0_GOTRELINDEX),
  LLD_KIND_STRING_END
};

#undef ELF_RELOC
```

Above code in Cpu0 lld support both endian for static link and dynamic link. The "#ifdef DLINKER" is for dynamic link support. The directory Cpu0 is for big endian and Cpu0el is for little endian. They are almost same. I believe the lld structure will change to support both endian but at this point, the best way to do both endian support is duplicate the directory.

2.2.3 LLD introduction

In general, linker do the Relocation Records Resolve as Chapter ELF support depicted, and optimization for those cannot finish in compiler stage. One of the optimization opportunities in linker is Dead Code Stripping which is explained in this section.

List the LLD project status as follows,

- The lld project aims to to be the built-in linker for clang/llvm. Currently, clang must invoke the system linker to produce executables.
- web site http://lld.llvm.org/
- Current Status
  - lld is in its early stages of development.
  - It can currently self host on Linux x86-64 with -static.
- How to build
  - cmake -DCMAKE_CXX_COMPILER=g++ -DCMAKE_C_COMPILER=gcc -DCMAKE_CXX_FLAGS=-std =c++11 -DCMAKE_BUILD_TYPE=Debug -G "Unix Makefiles" ../src/

This whole book focuses on backend design, and this chapter is same. To help readers understand the lld document, first we list the linking steps from lld web. After that, explain each step with the class of source code and what kind of Cpu0 backend implementation needed in each step. Since some of the following come from our understanding, please read the lld design web document first (only a few pages), http://lld.llvm.org/design.html, then reading the following to ensure you agree to our understanding.

How LLD do the linker job

- LLD structure
  - Internal structure Atom
    - Like llvm IR, lld operating and optimize in Atom.
  - ELF reader/writer, Mach-O reader/writer, COFF
    - Connect to any specific linker format by implement the concrete Read/Writer.
    - e.g. Implement Microsoft link format Reader/Writer => extend lld to support Microsoft link format.

- Atom
  - An atom is an indivisible chunk of code or data.
  - Typically each user written function or global variable is an atom.
  - In addition, the compiler may emit other atoms, such as for literal c-strings or floating point constants, or for runtime data structures like dwarf unwind info or pointers to initializers.
- Atoms classified:
  - The following Hello World code can be classified with these different kinds of Atoms as follows,

Atom example code

```
extern int printf(const char *format, ...);

int main(void)
{
  char *ptr = "Hello world!";

  printf("%s\n", ptr);
}
```

  - DefinedAtom
    - 95% of all atoms. This is a chunk of code or data
  - UndefinedAtom
    - printf in this example.
  - SharedLibraryAtom
    - Symbols defined in shared library (file *.so).
  - AbsoluteAtom
    - This is for embedded support where some stuff is implemented in ROM at some fixed address.

Linking Steps

- Command line processing
  - lld -flavor gnu -target cpu0-unknown-linux-gnu hello.o printf-stdarg.o -o a.out
- Parsing input files
  - ELF reader => create lld:File
- Resolving
  - dead code stripping
- Passes/Optimizations
  - Like llvm passes, give backend a chance to do something like optimization.
- Generate output file
  - Resolving Relocation Records – I guess in this step

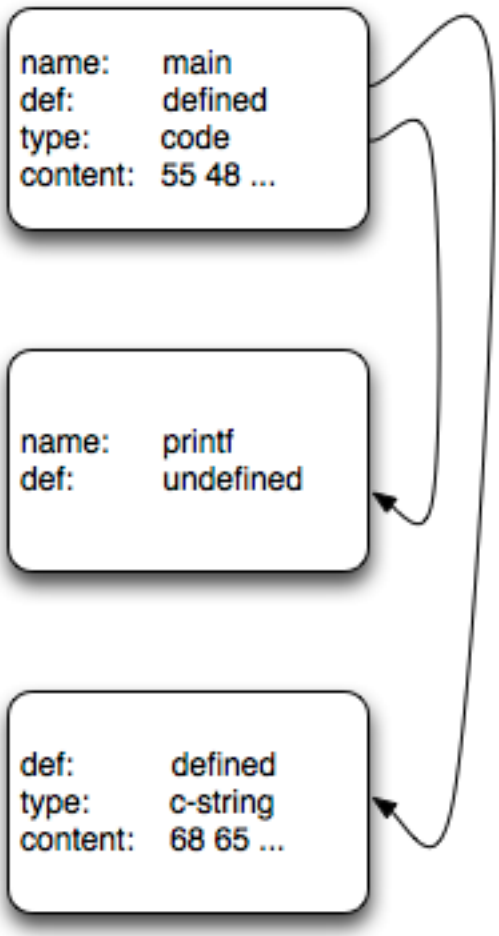

Figure 2.2: Atom classified (from lld web)

Command line processing

To support a new backend, the following code added for Command line processing.

lld/lib/ReaderWriter/ELF/ELFLinkingContext.cpp

```
uint16_t ELFLinkingContext::getOutputMachine() const {
  switch (getTriple().getArch()) {
  ...
  case llvm::Triple::cpu0:
    return llvm::ELF::EM_CPU0;
  default:
    llvm_unreachable("Unhandled arch");
  }
}

std::unique_ptr<ELFLinkingContext>
ELFLinkingContext::create(llvm::Triple triple) {
  switch (triple.getArch()) {
  ...
  case llvm::Triple::cpu0:
    return std::unique_ptr<ELFLinkingContext>(
        new lld::elf::Cpu0LinkingContext(triple));
  default:
    return nullptr;
  }
}
```

Parsing input files

- Input Files
  - A goal of lld is to be file format independent.
  - The lld::Reader is the base class for all object file readers
  - Every Reader subclass defines its own "options" class (for instance the mach-o Reader defines the class ReaderOptionsMachO). This options class is the one-and-only way to control how the Reader operates when parsing an input file into an Atom graph
- Reader
  - The base class lld::reader and the elf specific file format reader as follows,

    #### lld/lib/ReaderWriter/Reader.cpp

    ```
    ~/llvm/test/src/tools/lld/lib/ReaderWriter$ cat Reader.cpp
    ...
    #include "lld/ReaderWriter/Reader.h"

    #include "llvm/ADT/OwningPtr.h"
    #include "llvm/ADT/StringRef.h"
    #include "llvm/Support/MemoryBuffer.h"
    #include "llvm/Support/system_error.h"
    ```

```
namespace lld {
Reader::~Reader() {
}
} // end namespace lld
```

lld/lib/ReaderWriter/ELF/Reader.cpp

```
~/llvm/test/src/tools/lld/lib/ReaderWriter/ELF$ cat Reader.cpp
namespace lld {
namespace elf {
...
class ELFReader : public Reader {
public:
  ELFReader(const ELFLinkingContext &ctx)
      : lld::Reader(ctx), _elfLinkingContext(ctx) {}

  error_code parseFile(std::unique_ptr<MemoryBuffer> &mb,
                       std::vector<std::unique_ptr<File> > &result) const {
...
private:
  const ELFLinkingContext &_elfLinkingContext;
};
} // end namespace elf

std::unique_ptr<Reader> createReaderELF(const ELFLinkingContext &context) {
  return std::unique_ptr<Reader>(new elf::ELFReader(context));
}
} // end namespace lld
```

- lld::File representations
  - In memory, abstract C++ classes (lld::Atom, lld::Reference, and lld::File).
    - Data structure keeped in memory to be fast
  - textual (in YAML)
    - target-triple: x86_64-apple-darwin11
    - atoms:
      - name: _main
      - scope: global
      - type: code
      - content: [55, 48, 89, e5, 48, 8d, 3d, 00, 00, 00, 00, 30, c0, e8, 00, 00, 00, 00, 31, c0, 5d, c3]
  - binary format (“native”)
    - With this model for the native file format, files can be read and turned into the in-memory graph of lld::Atoms with just a few memory allocations. And the format can easily adapt over time to new features.

Resolving

- Dead code stripping (if requested) is done at the end of resolving.

- The linker does a simple mark-and-sweep. It starts with **"root"** atoms (like "main" in a main executable) and follows each references and marks each Atom that it visits as **"live"**.
- When done, all atoms not marked **"live"** are removed.

Dead code stripping - example (modified from llvm lto document web)

a.h

```
extern int foo1(void);
extern void foo2(void);
extern int foo4(void);
```

a.cpp

```
#include "a.h"

static signed int i = 0;

void foo2(void) {
  i = -1;
}

static int foo3() {
  return (10+foo4());
}

int foo1(void) {
  int data = 0;

  if (i < 0)
    data = foo3();

  data = data + 42;
  return data;
}
```

ch13_1.cpp

```
#include "a.h"

void ISR() {
  asm("ISR:");
  return;
}

int foo4(void) {
  return 5;
}

int main() {
  return foo1();
}
```

Above code can be reduced to Figure 2.3 to perform mark and swip in graph for Dead Code Stripping.

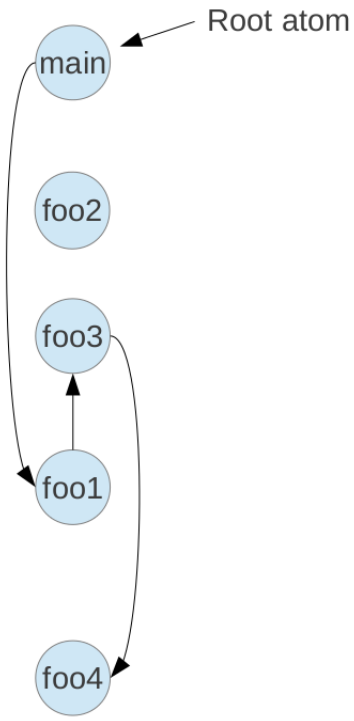

Figure 2.3: Atom classified (from lld web)

As above example, the foo2() is an isolated node without any reference. It's dead code and can be removed in linker optimization. We test this example by build-ch13_1.sh and find foo2() cannot be removed. There are two possibilities for this situation. One is we do not trigger lld dead code stripping optimization in command (the default is not do it). The other is lld hasn't implemented it yet at this point. It's reasonable since the lld is in its early stages of development. We didn't dig it more, since the Cpu0 backend tutorial just need a linker to finish Relocation Records Resolve and see how it runs on PC.

Remind, llvm-linker is the linker works on IR level linker optimization. Sometime when you got the obj file only (if you have a.o in this case), the native linker (such as lld) have the opportunity to do Dead Code Stripping while the IR linker hasn't.

Passes/Optimizations

- Passes
  - stub (PLT) generation
  - GOT instantiation
  - order_file optimization
  - branch island generation
  - branch shim generation
  - Objective-C optimizations (Darwin specific)
  - TLV instantiation (Darwin specific)

- DTrace probe processing (Darwin specific)
- compact unwind encoding (Darwin specific)

The Cpu0RelocationPass.cpp and Cpu0RelocationPass.h are example codes for lld backend Passes. The Relocation Pass structure shown as Figure 2.4. The Cpu0 backend has two Relocation Passes and both of them are children of RelocationPass. The StaticRelocationPass is for static linker and DynamicRelocationPass is for dynamic linker. We will see how to register a relocation pass according the staic or dynamic linker you like to do in next section.

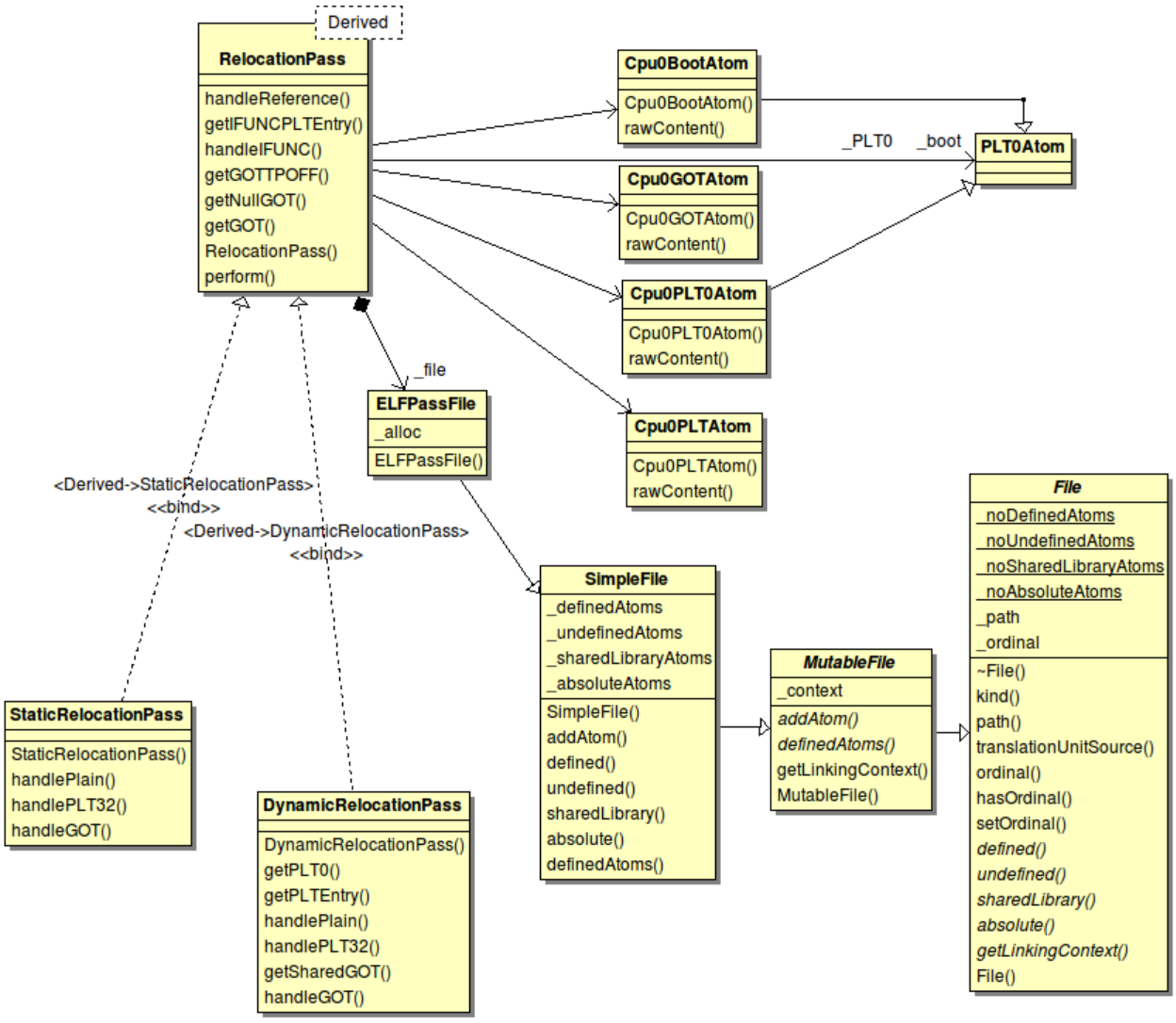

Figure 2.4: Cpu0 lld RelocationPass

All lld backends which want to handle the Relocation Records Resolve need to register a pass when the lld backend code is up. After register the pass, LLD will do last two steps, Passes/Optimization and Generate Output file, interactivly just like the "Parsing and Generating code" in compiler. LLD will do Passes/Optimization and call your lld backend hook function "applyRelocation()" (defined in Cpu0TargetRelocationHandler.cpp) to finish the address binding in linker stage. Based on this understanding, we believe the "applyRelocation()" is at the step of Generate output file rather than Passes/Optimization even LLD web document didn't indicate this.

The following code will register a pass when the lld backend code is up.

exlbt/lld/Cpu0/Cpu0RelocationPass.cpp

```
std::unique_ptr<Pass>
lld::elf::createCpu0RelocationPass(const Cpu0LinkingContext &ctx) {
  switch (ctx.getOutputELFType()) {
  case llvm::ELF::ET_EXEC:
  // when the output file is execution file: e.g. a.out
#ifdef DLINKER
    if (ctx.isDynamic())
    // when the a.out refer to shared object *.so
      return std::unique_ptr<Pass>(new DynamicRelocationPass(ctx));
    else
#endif // DLINKER
      return std::unique_ptr<Pass>(new StaticRelocationPass(ctx));
#ifdef DLINKER
  case llvm::ELF::ET_DYN:
  // when the output file is shared object: e.g. foobar.so
    return std::unique_ptr<Pass>(new DynamicRelocationPass(ctx));
#endif // DLINKER
  case llvm::ELF::ET_REL:
    return std::unique_ptr<Pass>();
  default:
    llvm_unreachable("Unhandled output file type");
  }
}
```

Generate Output File

- All concrete writers (e.g. ELF, mach-o, etc) are subclasses of the lld::Writer class.
- Every Writer subclass defines its own "options" class (for instance the mach-o Writer defines the class WriterOptionsMachO). This options class is the one-and-only way to control how the Writer operates when producing an output file from an Atom graph.
- Writer

lld/lib/ReaderWriter

```
~/llvm/test/src/tools/lld/lib/ReaderWriter$ cat Writer.cpp
...
#include "lld/Core/File.h"
#include "lld/ReaderWriter/Writer.h"

namespace lld {
Writer::Writer() {
}

Writer::~Writer() {
}

bool Writer::createImplicitFiles(std::vector<std::unique_ptr<File> > &) {
  return true;
}
} // end namespace lld
```

lld/lib/ReaderWriter

```
~/llvm/test/src/tools/lld/lib/ReaderWriter/ELF$ cat Writer.cpp
namespace lld {

std::unique_ptr<Writer> createWriterELF(const ELFLinkingContext &info) {
  using llvm::object::ELFType;
  ...
  switch (info.getOutputELFType()) {
  case llvm::ELF::ET_EXEC:
    if (info.is64Bits()) {
      if (info.isLittleEndian())
        return std::unique_ptr<Writer>(new
            elf::ExecutableWriter<ELFType<support::little, 8, true>>(info));
      else
        return std::unique_ptr<Writer>(new
                elf::ExecutableWriter<ELFType<support::big, 8, true>>(info));
...

} // namespace lld
```

After register a relocation pass, lld backend hook function "applyRelocation()" will be called by lld driver to finish the address binding in linker stage.

exlbt/lld/Cpu0/Cpu0RelocationHandler.cpp

```
ErrorOr<void> Cpu0TargetRelocationHandler::applyRelocation(
    ELFWriter &writer, llvm::FileOutputBuffer &buf, const lld::AtomLayout &atom,
    const Reference &ref) const {
  ...
  uint8_t *atomContent = buf.getBufferStart() + atom._fileOffset;
  uint8_t *location = atomContent + ref.offsetInAtom();
  uint64_t targetVAddress = writer.addressOfAtom(ref.target());
  uint64_t relocVAddress = atom._virtualAddr + ref.offsetInAtom();
  ...
  switch (ref.kind()) {
  case R_CPU0_NONE:
    break;
  case R_CPU0_HI16:
    relocHI16(location, relocVAddress, targetVAddress, ref.addend());
    break;
  case R_CPU0_LO16:
    relocLO16(location, relocVAddress, targetVAddress, ref.addend());
    break;
  ...
  case R_CPU0_PC24:
    relocPC24(location, relocVAddress, targetVAddress, ref.addend());
    break;
  ...
  }
  return error_code::success();
}
```

exlbt/input/ch_hello.c

```
extern int printf(const char *format, ...);

int main(void)
{
  char *ptr = "Hello world!";

  printf("%s\n", ptr);
}
```

exlbt/input/build-hello.sh

```
#!/usr/bin/env bash

source functions.sh

sh_name=build-hello.sh
argNum=$#
arg1=$1
arg2=$2

prologue;

clang -target mips-unknown-linux-gnu -c start.cpp -emit-llvm -o start.bc
clang -target mips-unknown-linux-gnu -c debug.cpp -emit-llvm -o debug.bc
clang -target mips-unknown-linux-gnu -c printf-stdarg-def.c -emit-llvm \
-o printf-stdarg-def.bc
clang -target mips-unknown-linux-gnu -c printf-stdarg.c -emit-llvm \
-o printf-stdarg.bc
clang -target mips-unknown-linux-gnu -c ch_hello.c -emit-llvm -o ch_hello.bc
${TOOLDIR}/llc -march=cpu0${endian} -mcpu=${CPU} -relocation-model=static \
-filetype=obj start.bc -o start.cpu0.o
${TOOLDIR}/llc -march=cpu0${endian} -mcpu=${CPU} -relocation-model=static \
-filetype=obj debug.bc -o debug.cpu0.o
${TOOLDIR}/llc -march=cpu0${endian} -mcpu=${CPU} -relocation-model=static \
-filetype=obj printf-stdarg-def.bc -o printf-stdarg-def.cpu0.o
${TOOLDIR}/llc -march=cpu0${endian} -mcpu=${CPU} -relocation-model=static \
-filetype=obj printf-stdarg.bc -o printf-stdarg.cpu0.o
${TOOLDIR}/llc -march=cpu0${endian} -mcpu=${CPU} -relocation-model=static \
-filetype=obj ch_hello.bc -o ch_hello.cpu0.o
${TOOLDIR}/llc -march=cpu0${endian} -mcpu=${CPU} -relocation-model=static \
-filetype=obj lib_cpu0.ll -o lib_cpu0.o
${TOOLDIR}/lld -flavor gnu -target cpu0${endian}-unknown-linux-gnu \
start.cpu0.o debug.cpu0.o printf-stdarg-def.cpu0.o printf-stdarg.cpu0.o \
ch_hello.cpu0.o lib_cpu0.o -o a.out

epilogue;
```

exlbt/verilog/Cpu0.hex

```
...
/*printf:*/
/*      b4:*/ 09 dd ff e0                                  /* addiu   $sp, $sp, -32*/
...
```

```
/*main:*/
/*     9e0:*/ 09 dd ff e8                                  /* addiu   $sp, $sp, -24*/
...
/*     9f0:*/ 0f 20 00 00                                  /* lui     $2, 0*/
/*     9f4:*/ 0d 22 0b 9f                                  /* ori     $2, $2, 2975*/
...
/*     a0c:*/ 3b ff f6 a4                                  /* jsub    16774820*/
...
/*Contents of section .rodata:*/
/*0b98 */28 6e 75 6c  6c 29 00 48  65 6c 6c 6f  20 77 6f 72 /*  (null).Hello wor*/
/*0ba8 */6c 64 21 00  25 73 0a 00   /*  ld!.\%s..*/
```

As you can see, applyRelocation() get four values for the Relocation Records Solving. When meets R_CPU0_LO16, targetVAddress is the only one value needed for this Relocation Solving in these four values. For this ch_hello.c example code, the lld set the "Hello world!" string begin at 0x0b98+7=0x0b9f. So, targetVAddress is 0x0b9f. These two instructions "lui" and "ori" at address 0x9f0 and 0x9f4, respectively, loading the address of "Hello world!" string to register $2. The "lui" got the HI 16 bits while the "ori" got the LO 16 bits of address of "Hello world!" string. This "lui" Relocation Record, R_CPU0_HI16, is 0 since the HI 16 bits of 0xb9f is 0 while the "ori" Relocation Record, R_CPU0_LO16, is 0xb9f. The instruction "jsub" at 0xa0c is an instruction jump to printf(). This instruction is a PC relative address Relocation Record, R_CPU0_PC24, while the R_CPU0_LO16 is an absolute address Relocation Record. To solve this Relocation Record, it needs "location" in addition to targetVAddress. In this case, the targetVAddress is 0xb4 where is the printf subroutine start address and the location is 0xa0c since the instruction "jsub" sit at this address. The R_CPU0_PC24 is solved by (0xb4 - (0xa0c + 4) = 0xf6a4 for 16 bits with sign extension) since after this "jsub" instruction executed the PC counter is (0xa0c+4). To +4 at current instruction because PC counter increased at instruction fetch stage in Verilog design.

Remind, we explain the Relocation Records Solving according file cpu0.hex list as above because the the Cpu0 machine boot at memory address 0x0 while the elf text section or plt section as follows start at 0x140. The 0x0 is the header of machine architecture information. The elf2hex code must keeps the address relative distance between text and plt sections just like the Cpu0 elf2hex.h did. The .rodata and other data sections are binding with absolute address, Cpu0 elf2hex must keeps them as the same address of elf.

For the following example code run, the book example code, exlbt.tar.gz, untared in directory /Users/Jonathan/test/lbt/. The Cpu0 backend code, lbdex.tar.gz, untared in the same directory too. The lbdex.tar.gz can be get from the bottom of web, http://jonathan2251.github.io/lbd/index.html.

```
1-160-136-173:input Jonathan$ pwd
/Users/Jonathan/test/lbt/exlbt/input
1-160-136-173:input Jonathan$ ls ../..
... exlbt ... lbdex ...
/Users/Jonathan/test/lbt/exlbt/input
1-160-136-173:input Jonathan$ bash build-hello.sh cpu032I be
1-160-136-173:input Jonathan$ /Users/Jonathan/llvm/test/cmake_debug_build/
Debug/bin/llvm-objdump -s a.out
...                 .
Contents of section .plt:
 0140 3600000c 36000004 36000004 36ffffc  6...6...6...6...
Contents of section .text:
 0150 09ddfff8 02ed0004 02cd0000 11cd0000  ................
...
Contents of section .rodata:
 0b98 286e756c 6c290048 656c6c6f 20776f72  (null).Hello wor
 0ba8 6c642100 25730a00                    ld!.%s..
```

Next section will show you how to design your lld backend and register a pass for Relocation Records Solve in details through Cpu0 backend code explantation.

2.2.4 Static linker

Let's run the static linker first and explain it next.

Run

File printf-stdarg.c come from internet download which is GPL2 license. GPL2 is more restricted than LLVM license. File printf-stdarg-1.c is the file for testing the printf() function which implemented on PC OS platform. Let's run printf-stdarg-2.cpp on Cpu0 and compare it against the result of PC's printf() as below.

exlbt/input/printf-stdarg-1.c

```
/*
  Copyright 2001, 2002 Georges Menie (www.menie.org)
  stdarg version contributed by Christian Ettinger

    This program is free software; you can redistribute it and/or modify
    it under the terms of the GNU Lesser General Public License as published by
    the Free Software Foundation; either version 2 of the License, or
    (at your option) any later version.

    This program is distributed in the hope that it will be useful,
    but WITHOUT ANY WARRANTY; without even the implied warranty of
    MERCHANTABILITY or FITNESS FOR A PARTICULAR PURPOSE.  See the
    GNU Lesser General Public License for more details.

    You should have received a copy of the GNU Lesser General Public License
    along with this program; if not, write to the Free Software
    Foundation, Inc., 59 Temple Place, Suite 330, Boston, MA  02111-1307  USA
*/

/*
  putchar is the only external dependency for this file,
  if you have a working putchar, leave it commented out.
  If not, uncomment the define below and
  replace outbyte(c) by your own function call.

#define putchar(c) outbyte(c)
*/

// gcc printf-stdarg-1.c
// ./a.out

#include <stdio.h>

#define TEST_PRINTF

#ifdef TEST_PRINTF
int main(void)
{
  char *ptr = "Hello world!";
  char *np = 0;
  int i = 5;
  unsigned int bs = sizeof(int)*8;
  int mi;
  char buf[80];
```

```
  mi = (1 << (bs-1)) + 1;
  printf("%s\n", ptr);
  printf("printf test\n");
  printf("%s is null pointer\n", np);
  printf("%d = 5\n", i);
  printf("%d = - max int\n", mi);
  printf("char %c = 'a'\n", 'a');
  printf("hex %x = ff\n", 0xff);
  printf("hex %02x = 00\n", 0);
  printf("signed %d = unsigned %u = hex %x\n", -3, -3, -3);
  printf("%d %s(s)%", 0, "message");
  printf("\n");
  printf("%d %s(s) with %%\n", 0, "message");
  sprintf(buf, "justif: \"%-10s\"\n", "left"); printf("%s", buf);
  sprintf(buf, "justif: \"%10s\"\n", "right"); printf("%s", buf);
  sprintf(buf, " 3: %04d zero padded\n", 3); printf("%s", buf);
  sprintf(buf, " 3: %-4d left justif.\n", 3); printf("%s", buf);
  sprintf(buf, " 3: %4d right justif.\n", 3); printf("%s", buf);
  sprintf(buf, "-3: %04d zero padded\n", -3); printf("%s", buf);
  sprintf(buf, "-3: %-4d left justif.\n", -3); printf("%s", buf);
  sprintf(buf, "-3: %4d right justif.\n", -3); printf("%s", buf);

  return 0;
}

/*
 * if you compile this file with
 *   gcc -Wall $(YOUR_C_OPTIONS) -DTEST_PRINTF -c printf.c
 * you will get a normal warning:
 *   printf.c:214: warning: spurious trailing '%' in format
 * this line is testing an invalid % at the end of the format string.
 *
 * this should display (on 32bit int machine) :
 *
 * Hello world!
 * printf test
 * (null) is null pointer
 * 5 = 5
 * -2147483647 = - max int
 * char a = 'a'
 * hex ff = ff
 * hex 00 = 00
 * signed -3 = unsigned 4294967293 = hex fffffffd
 * 0 message(s)
 * 0 message(s) with %
 * justif: "left      "
 * justif: "     right"
 *  3: 0003 zero padded
 *  3: 3    left justif.
 *  3:    3 right justif.
 * -3: -003 zero padded
 * -3: -3   left justif.
 * -3:   -3 right justif.
 */

#endif
```

exlbt/input/printf-stdarg-2.cpp

```
#include "debug.h"
#include "print.h"

#define TEST_PRINTF

extern "C" int putchar(int c);

extern "C" {
#include "printf-stdarg.c"
}
```

exlbt/input/printf-stdarg-def.c

```
#include "print.h"

// Definition putchar(int c) for printf-stdarg.c
// For memory IO
int putchar(int c)
{
  char *p = (char*)OUT_MEM;
  *p = c;

  return 0;
}
```

exlbt/input/printf-stdarg.c

```
/*
  Copyright 2001, 2002 Georges Menie (www.menie.org)
  stdarg version contributed by Christian Ettinger

    This program is free software; you can redistribute it and/or modify
    it under the terms of the GNU Lesser General Public License as published by
    the Free Software Foundation; either version 2 of the License, or
    (at your option) any later version.

    This program is distributed in the hope that it will be useful,
    but WITHOUT ANY WARRANTY; without even the implied warranty of
    MERCHANTABILITY or FITNESS FOR A PARTICULAR PURPOSE.  See the
    GNU Lesser General Public License for more details.

    You should have received a copy of the GNU Lesser General Public License
    along with this program; if not, write to the Free Software
    Foundation, Inc., 59 Temple Place, Suite 330, Boston, MA  02111-1307  USA
*/

/*
  putchar is the only external dependency for this file,
  if you have a working putchar, leave it commented out.
  If not, uncomment the define below and
  replace outbyte(c) by your own function call.
```

```
#define putchar(c) outbyte(c)
*/

#include <stdarg.h>

static void printchar(char **str, int c)
{
  extern int putchar(int c);

  if (str) {
    **str = c;
    ++(*str);
  }
  else (void)putchar(c);
}

#define PAD_RIGHT 1
#define PAD_ZERO 2

static int prints(char **out, const char *string, int width, int pad)
{
  register int pc = 0, padchar = ' ';

  if (width > 0) {
    register int len = 0;
    register const char *ptr;
    for (ptr = string; *ptr; ++ptr) ++len;
    if (len >= width) width = 0;
    else width -= len;
    if (pad & PAD_ZERO) padchar = '0';
  }
  if (!(pad & PAD_RIGHT)) {
    for ( ; width > 0; --width) {
      printchar (out, padchar);
      ++pc;
    }
  }
  for ( ; *string ; ++string) {
    printchar (out, *string);
    ++pc;
  }
  for ( ; width > 0; --width) {
    printchar (out, padchar);
    ++pc;
  }

  return pc;
}

/* the following should be enough for 32 bit int */
#define PRINT_BUF_LEN 12

static int printi(char **out, int i, int b, int sg, int width, int pad, int letbase)
{
  char print_buf[PRINT_BUF_LEN];
  register char *s;
  register int t, neg = 0, pc = 0;
  register unsigned int u = i;
```

```
  if (i == 0) {
    print_buf[0] = '0';
    print_buf[1] = '\0';
    return prints (out, print_buf, width, pad);
  }

  if (sg && b == 10 && i < 0) {
    neg = 1;
    u = -i;
  }

  s = print_buf + PRINT_BUF_LEN-1;
  *s = '\0';

  while (u) {
    t = u % b;
    if( t >= 10 )
      t += letbase - '0' - 10;
    *--s = t + '0';
    u /= b;
  }

  if (neg) {
    if( width && (pad & PAD_ZERO) ) {
      printchar (out, '-');
      ++pc;
      --width;
    }
    else {
      *--s = '-';
    }
  }

  return pc + prints (out, s, width, pad);
}

static int print(char **out, const char *format, va_list args )
{
  register int width, pad;
  register int pc = 0;
  char scr[2];

  for (; *format != 0; ++format) {
    if (*format == '%') {
      ++format;
      width = pad = 0;
      if (*format == '\0') break;
      if (*format == '%') goto out;
      if (*format == '-') {
        ++format;
        pad = PAD_RIGHT;
      }
      while (*format == '0') {
        ++format;
        pad |= PAD_ZERO;
      }
      for ( ; *format >= '0' && *format <= '9'; ++format) {
        width *= 10;
```

```
        width += *format - '0';
      }
      if( *format == 's' ) {
        register char *s = (char *)va_arg( args, int );
        pc += prints (out, s?s:"(null)", width, pad);
        continue;
      }
      if( *format == 'd' ) {
        pc += printi (out, va_arg( args, int ), 10, 1, width, pad, 'a');
        continue;
      }
      if( *format == 'x' ) {
        pc += printi (out, va_arg( args, int ), 16, 0, width, pad, 'a');
        continue;
      }
      if( *format == 'X' ) {
        pc += printi (out, va_arg( args, int ), 16, 0, width, pad, 'A');
        continue;
      }
      if( *format == 'u' ) {
        pc += printi (out, va_arg( args, int ), 10, 0, width, pad, 'a');
        continue;
      }
      if( *format == 'c' ) {
        /* char are converted to int then pushed on the stack */
        scr[0] = (char)va_arg( args, int );
        scr[1] = '\0';
        pc += prints (out, scr, width, pad);
        continue;
      }
    }
    else {
    out:
      printchar (out, *format);
      ++pc;
    }
  }
  if (out) **out = '\0';
  va_end( args );
  return pc;
}

int printf(const char *format, ...)
{
        va_list args;

        va_start( args, format );
        return print( 0, format, args );
}

int sprintf(char *out, const char *format, ...)
{
        va_list args;

        va_start( args, format );
        return print( &out, format, args );
}
```

```
#ifdef TEST_PRINTF
int main(void)
{
  char *ptr = "Hello world!";
  char *np = 0;
  int i = 5;
  unsigned int bs = sizeof(int)*8;
  int mi;
  char buf[80];

  mi = (1 << (bs-1)) + 1;
  printf("%s\n", ptr);
  printf("printf test\n");
  printf("%s is null pointer\n", np);
  printf("%d = 5\n", i);
  printf("%d = - max int\n", mi);
  printf("char %c = 'a'\n", 'a');
  printf("hex %x = ff\n", 0xff);
  printf("hex %02x = 00\n", 0);
  printf("signed %d = unsigned %u = hex %x\n", -3, -3, -3);
  printf("%d %s(s)%", 0, "message");
  printf("\n");
  printf("%d %s(s) with %%\n", 0, "message");
  sprintf(buf, "justif: \"%-10s\"\n", "left"); printf("%s", buf);
  sprintf(buf, "justif: \"%10s\"\n", "right"); printf("%s", buf);
  sprintf(buf, " 3: %04d zero padded\n", 3); printf("%s", buf);
  sprintf(buf, " 3: %-4d left justif.\n", 3); printf("%s", buf);
  sprintf(buf, " 3: %4d right justif.\n", 3); printf("%s", buf);
  sprintf(buf, "-3: %04d zero padded\n", -3); printf("%s", buf);
  sprintf(buf, "-3: %-4d left justif.\n", -3); printf("%s", buf);
  sprintf(buf, "-3: %4d right justif.\n", -3); printf("%s", buf);

  return 0;
}

/*
 * if you compile this file with
 *   gcc -Wall $(YOUR_C_OPTIONS) -DTEST_PRINTF -c printf.c
 * you will get a normal warning:
 *   printf.c:214: warning: spurious trailing '%' in format
 * this line is testing an invalid % at the end of the format string.
 *
 * this should display (on 32bit int machine) :
 *
 * Hello world!
 * printf test
 * (null) is null pointer
 * 5 = 5
 * -2147483647 = - max int
 * char a = 'a'
 * hex ff = ff
 * hex 00 = 00
 * signed -3 = unsigned 4294967293 = hex fffffffd
 * 0 message(s)
 * 0 message(s) with %
 * justif: "left      "
 * justif: "     right"
 *  3: 0003 zero padded
```

```
 *  3: 3    left justif.
 *  3:    3 right justif.
 * -3: -003 zero padded
 * -3: -3   left justif.
 * -3:   -3 right justif.
 */

#endif
```

exlbt/input/start.cpp

```
#include "dynamic_linker.h"
#include "start.h"

extern int main();

// Real entry (first instruction) is from cpu0BootAtomContent of
// Cpu0RelocationPass.cpp jump to asm("start:") of start.cpp.
void start() {
  asm("start:");

  asm("lui $sp, 0x6");
  asm("addiu $sp, $sp, 0xfffc");
  int *gpaddr;
  gpaddr = (int*)GPADDR;
  __asm__ __volatile__("ld  $gp, %0"
                       : // no output register, specify output register to $gp
                       :"m"(*gpaddr)
                       );
  initRegs();
  main();
  asm("addiu $lr, $ZERO, -1");
  asm("ret $lr");
}
```

exlbt/input/lib_cpu0.ll

```
; The @_start() exist to prevent lld linker error.
; Real entry (first instruction) is from cpu0BootAtomContent of
; Cpu0RelocationPass.cpp jump to asm("start:") of start.cpp.
define void @_start() nounwind {
entry:
  ret void
}

define void @__start() nounwind {
entry:
  ret void
}

define void @__stack_chk_fail() nounwind {
entry:
  ret void
}
```

```
define void @__stack_chk_guard() nounwind {
entry:
  ret void
}

define void @_ZdlPv() nounwind {
entry:
  ret void
}

define void @__dso_handle() nounwind {
entry:
  ret void
}

define void @_ZNSt8ios_base4InitC1Ev() nounwind {
entry:
  ret void
}

define void @__cxa_atexit() nounwind {
entry:
  ret void
}

define void @_ZTVN10__cxxabiv120__si_class_type_infoE() nounwind {
entry:
  ret void
}

define void @_ZTVN10__cxxabiv117__class_type_infoE() nounwind {
entry:
  ret void
}

define void @_Znwm() nounwind {
entry:
  ret void
}

define void @__cxa_pure_virtual() nounwind {
entry:
  ret void
}

define void @_ZNSt8ios_base4InitD1Ev() nounwind {
entry:
  ret void
}
```

exlbt/input/functions.sh

```
prologue() {
  LBDEXDIR=../../lbdex

  if [ $argNum == 0 ]; then
```

```
    echo "useage: bash $sh_name cpu_type endian"
    echo "  cpu_type: cpu032I or cpu032II"
    echo "  endian: be (big endian, default) or le (little endian)"
    echo "for example:"
    echo "  bash build-slinker.sh cpu032I be"
    exit 1;
  fi
  if [ $arg1 != cpu032I ] && [ $arg1 != cpu032II ]; then
    echo "1st argument is cpu032I or cpu032II"
    exit 1
  fi

  INCDIR=../../lbdex/input
  OS=`uname -s`
  echo "OS =" ${OS}

  if [ "$OS" == "Linux" ]; then
    TOOLDIR=~/llvm/test/cmake_debug_build/bin
  else
    TOOLDIR=~/llvm/test/cmake_debug_build/Debug/bin
  fi

  CPU=$arg1
  echo "CPU =" "${CPU}"

  if [ "$arg2" != "" ] && [ $arg2 != le ] && [ $arg2 != be ]; then
    echo "2nd argument is be (big endian, default) or le (little endian)"
    exit 1
  fi
  if [ "$arg2" == "" ] || [ $arg2 == be ]; then
    endian=
  else
    endian=el
  fi
  echo "endian =" "${endian}"

  bash clean.sh
}

isLittleEndian() {
  echo "endian = " "$endian"
  if [ "$endian" == "LittleEndian" ] ; then
    le="true"
  elif [ "$endian" == "BigEndian" ] ; then
    le="false"
  else
    echo "!endian unknown"
    exit 1
  fi
}

elf2hex() {
  ${TOOLDIR}/llvm-objdump -elf2hex -le=${le} a.out > ${LBDEXDIR}/verilog/cpu0.hex
  if [ ${le} == "true" ] ; then
    echo "1   /* 0: big endian, 1: little endian */" > ${LBDEXDIR}/verilog/cpu0.config
  else
    echo "0   /* 0: big endian, 1: little endian */" > ${LBDEXDIR}/verilog/cpu0.config
  fi
```

```
  cat ${LBDEXDIR}/verilog/cpu0.config
}

epilogue() {
  endian=`${TOOLDIR}/llvm-readobj -h a.out|grep "DataEncoding"|awk '{print $2}'`
  isLittleEndian;
  elf2hex;
}
```

exlbt/input/build-printf-stdarg-2.sh

```
#!/usr/bin/env bash

source functions.sh

sh_name=build-printf-stdarg-2.sh
argNum=$#
arg1=$1
arg2=$2

prologue;

clang -target mips-unknown-linux-gnu -c start.cpp -emit-llvm -o start.bc
clang -target mips-unknown-linux-gnu -c debug.cpp -emit-llvm -o debug.bc
clang -target mips-unknown-linux-gnu -c printf-stdarg-def.c -emit-llvm \
-o printf-stdarg-def.bc
clang -target mips-unknown-linux-gnu -c printf-stdarg-2.cpp -emit-llvm -o \
printf-stdarg-2.bc
${TOOLDIR}/llc -march=cpu0${endian} -mcpu=${CPU} -relocation-model=static \
-filetype=obj start.bc -o start.cpu0.o
${TOOLDIR}/llc -march=cpu0${endian} -mcpu=${CPU} -relocation-model=static \
-filetype=obj debug.bc -o debug.cpu0.o
${TOOLDIR}/llc -march=cpu0${endian} -mcpu=${CPU} -relocation-model=static \
-filetype=obj printf-stdarg-def.bc -o printf-stdarg-def.cpu0.o
${TOOLDIR}/llc -march=cpu0${endian} -mcpu=${CPU} -relocation-model=static \
-filetype=obj printf-stdarg-2.bc -o printf-stdarg-2.cpu0.o
${TOOLDIR}/llc -march=cpu0${endian} -mcpu=${CPU} -relocation-model=static \
-filetype=obj lib_cpu0.ll -o lib_cpu0.o
${TOOLDIR}/lld -flavor gnu -target cpu0${endian}-unknown-linux-gnu \
start.cpu0.o debug.cpu0.o printf-stdarg-def.cpu0.o printf-stdarg-2.cpu0.o \
lib_cpu0.o -o a.out

epilogue;
```

The verilog/cpu0Is.v support cmp instruction and static linker as follows,

lbdex/verilog/cpu0Is.v

```
// TRACE: Display the memory contents of the loaded program and data
//`define TRACE

`include "cpu0.v"
```

The verilog/cpu0IIs.v support slt instruction and static linker as follows,

lbdex/verilog/cpu0IIs.v

```
`define CPU0II
// TRACE: Display the memory contents of the loaded program and data
//`define TRACE

`include "cpu0.v"
```

The build-printf-stdarg-2.sh is for my PC setting. Please change this script to the directory of your llvm/lld setting. After that run static linker example code as follows,

```
1-160-136-173:input Jonathan$ pwd
/Users/Jonathan/test/lbt/exlbt/input
1-160-136-173:input Jonathan$ bash build-printf-stdarg-2.sh cpu032I be
In file included from printf-stdarg-2.cpp:11:
./printf-stdarg.c:206:15: warning: conversion from string literal to 'char *'
is deprecated [-Wdeprecated-writable-strings]
  char *ptr = "Hello world!";
              ^
1 warning generated.

1-160-136-173:input Jonathan$ cd ../../lbdex/verilog/
1-160-136-173:verilog Jonathan$ pwd
/Users/Jonathan/test/lbt/lbdex/lbdex/verilog
1-160-136-173:verilog Jonathan$ bash clean.sh
1-160-136-173:verilog Jonathan$ iverilog -o cpu0II cpu0IIs.v
Hello world!
printf test
(null) is null pointer
5 = 5
-2147483647 = - max int
char a = 'a'
hex ff = ff
hex 00 = 00
signed -3 = unsigned 4294967293 = hex fffffffd
0 message(s)
0 message(s) with \%
justif: "left      "
justif: "     right"
 3: 0003 zero padded
 3: 3    left justif.
 3:    3 right justif.
-3: -003 zero padded
```

Let's check the result with PC program printf-stdarg-1.c output as follows,

```
1-160-136-173:input Jonathan$ clang printf-stdarg-1.c
printf-stdarg-1.c:58:19: warning: incomplete format specifier [-Wformat]
  printf("%d %s(s)%", 0, "message");
                  ^
1 warning generated.
1-160-136-173:input Jonathan$ ./a.out
Hello world!
printf test
(null) is null pointer
5 = 5
-2147483647 = - max int
char a = 'a'
```

```
hex ff = ff
hex 00 = 00
signed -3 = unsigned 4294967293 = hex fffffffd
0 message(s)
0 message(s) with \%
justif: "left      "
justif: "     right"
 3: 0003 zero padded
 3: 3    left justif.
 3:    3 right justif.
-3: -003 zero padded
-3: -3   left justif.
-3:   -3 right justif.
```

They are same. You can verify the slt instructions is work fine too by change variable cpu from cpu032I to cpu032II as follows,

exlbt/input/build-printf-stdarg-2.sh

```
1-160-136-173:verilog Jonathan$ pwd
/Users/Jonathan/test/lbt/lbdex/verilog
1-160-136-173:verilog Jonathan$ cd ../../exlbt/input
1-160-136-173:input Jonathan$ pwd
/Users/Jonathan/test/lbt/exlbt/input
1-160-136-173:input Jonathan$ bash build-printf-stdarg-2.sh cpu032II be
...
1-160-136-173:input Jonathan$ cd ../lbdex/verilog/
1-160-136-173:verilog Jonathan$ ./cpu0IIs
```

The verilog machine cpu0IIs include all instructions of cpu032I and add slt, beq, ..., instructions. Run build-printf-stdarg-2.sh with cpu=cpu032II will generate slt, beq and bne instructions instead of cmp, jeq, ... instructions.

With the printf() of GPL source code, we can program more test code with it to verify the previous llvm Cpu0 backend generated program. The following code is for this purpose.

exlbt/input/debug.cpp

```
#include "debug.h"

extern "C" int printf(const char *format, ...);

// With read variable form asm, such as sw in this example, the function,
// ISR_Handler() must entry from beginning. The ISR() enter from "ISR:" will
// has incorrect value for reload instruction in offset.
// For example, the correct one is:
//   "addiu $sp, $sp, -12"
//   "mov $fp, $sp"
// ISR:
//   "ld $2, 32($fp)"
// Go to ISR directly, then the $fp is 12+ than original, then it will get
//   "ld $2, 20($fp)" actually.
void ISR_Handler() {
  SAVE_REGISTERS;
  asm("lui $7, 0xffff");
  asm("ori $7, $7, 0xfdff");
```

```
  asm("and $sw, $sw, $7"); // clear 'IE

  volatile int sw;
  __asm__ __volatile__("addiu %0, $sw, 0"
                       :"=r"(sw)
                       );
  int interrupt = (sw & INT);
  int softint = (sw & SOFTWARE_INT);
  int overflow = (sw & OVERFLOW);
  int int1 = (sw & INT1);
  int int2 = (sw & INT2);
  if (interrupt) {
    if (softint) {
      if (overflow) {
        printf("Overflow exception\n");
        CLEAR_OVERFLOW;
      }
      else {
        printf("Software interrupt\n");
      }
      CLEAR_SOFTWARE_INT;
    }
    else if (int1) {
      printf("Harware interrupt 0\n");
      asm("lui $7, 0xffff");
      asm("ori $7, $7, 0x7fff");
      asm("and $sw, $sw, $7");
    }
    else if (int2) {
      printf("Harware interrupt 1\n");
      asm("lui $7, 0xfffe");
      asm("ori $7, $7, 0xffff");
      asm("and $sw, $sw, $7");
    }
    asm("lui $7, 0xffff");
    asm("ori $7, $7, 0xdfff");
    asm("and $sw, $sw, $7"); // clear 'I
  }
  asm("ori $sw, $sw, 0x200"); // int enable
  RESTORE_REGISTERS;
  return;
}

void ISR() {
  asm("ISR:");
  asm("lui $at, 7");
  asm("ori $at, $at, 0xff00");
  asm("st $14, 48($at)");
  ISR_Handler();
  asm("lui $at, 7");
  asm("ori $at, $at, 0xff00");
  asm("ld $14, 48($at)");
  asm("c0mov $pc, $epc");
}

void int_sim() {
  asm("ori $sw, $sw, 0x200"); // int enable
  asm("ori $sw, $sw, 0x2000"); // set interrupt
```

```
  asm("ori $sw, $sw, 0x4000"); // Software interrupt
  asm("ori $sw, $sw, 0x200"); // int enable
  asm("ori $sw, $sw, 0x2000"); // set interrupt
  asm("ori $sw, $sw, 0x8000"); // hardware interrupt 0
  asm("ori $sw, $sw, 0x200"); // int enable
  asm("ori $sw, $sw, 0x2000"); // set interrupt
  asm("lui $at, 1");
  asm("or $sw, $sw, $at"); // hardware interrupt 1
  return;
}
```

exlbt/input/ch_lld_staticlink.h

```
#include "debug.h"
#include "print.h"

#define PRINT_TEST

extern "C" int printf(const char *format, ...);
extern "C" int sprintf(char *out, const char *format, ...);

extern unsigned char sBuffer[4];
extern int test_overflow();
extern int test_add_overflow();
extern int test_sub_overflow();
extern int test_ctrl2();
extern int select_1();
extern int select_2();
extern int select_3();
extern int test_select_global_pic();
extern int test_tailcall(int a);
extern int test_alloc();

extern int test_staticlink();
```

exlbt/input/ch_lld_staticlink.cpp

```
#include "ch6_1.cpp"
#include "ch9_2_1.cpp"
#include "ch9_2_2.cpp"
#include "ch9_3_2.cpp"
#include "ch11_2.cpp"
#include "ch12_inherit.cpp"

int verify_test_ctrl2()
{
  int a = -1;
  int b = -1;
  int c = -1;
  int d = -1;

  sBuffer[0] = (unsigned char)0x35;
  sBuffer[1] = (unsigned char)0x35;
  a = test_ctrl2();
  sBuffer[0] = (unsigned char)0x30;
```

```
  sBuffer[1] = (unsigned char)0x29;
  b = test_ctrl2();
  sBuffer[0] = (unsigned char)0x35;
  sBuffer[1] = (unsigned char)0x35;
  c = test_ctrl2();
  sBuffer[0] = (unsigned char)0x34;
  d = test_ctrl2();
  printf("test_ctrl2(): a = %d, b = %d, c = %d, d = %d", a, b, c, d);
  if (a == 1 && b == 0 && c == 1 && d == 0)
    printf(", PASS\n");
  else
    printf(", FAIL\n");

  return 0;
}

int test_staticlink()
{
  int a = 0;

  a = test_add_overflow();
  a = test_sub_overflow();
  a = test_global();  // gI = 100
  printf("global variable gI = %d", a);
  if (a == 100)
    printf(", PASS\n");
  else
    printf(", FAIL\n");
  a = verify_test_ctrl2();
  a = select_1();
  printf("select_1() = %d\n", a); // a = 1
  a = select_2();
  printf("select_2() = %d\n", a); // a = 1
  a = select_3();
  printf("select_3() = %d\n", a); // a = 1
  a = test_select_global_pic(); // test global of pic llc -O1 option
  printf("test_select_global_pic() = %d", a); // a = 100
  if (a == 100)
    printf(", PASS\n");
  else
    printf(", FAIL\n");
  a = test_tailcall(5);
  printf("test_tailcall(5) = %d", a); // a = 120
  if (a == 120)
    printf(", PASS\n");
  else
    printf(", FAIL\n");
  a = test_func_arg_struct();
  a = test_contructor();
  a = test_template();
  printf("test_template() = %d", a); // a = 15
  if (a == 15)
    printf(", PASS\n");
  else
    printf(", FAIL\n");
  a = test_alloc();  // 31
  printf("test_alloc() = %d", a);
  if (a == 31)
```

```
    printf(", PASS\n");
  else
    printf(", FAIL\n");
  a = test_inlineasm();
  printf("test_inlineasm() = %d", a); // a = 53
  if (a == 53)
    printf(", PASS\n");
  else
    printf(", FAIL\n");
  a = test_cpp_polymorphism();
  printf("test_cpp_polymorphism() = %d", a); // a = 0
  if (a == 0)
    printf(", PASS\n");
  else
    printf(", FAIL\n");
  test_build();

  int_sim();

  return 0;
}
```

exlbt/input/ch_slinker.cpp

```
//#define TEST_SELECT

#include "ch_nolld.h"
#include "ch_lld_staticlink.h"

int main()
{
  bool pass = true;
  pass = test_nolld();
  if (pass)
    printf("test_nolld(): PASS\n");
  else
    printf("test_nolld(): FAIL\n");
  pass = true;
  pass = test_staticlink();

  return pass;
}

#include "ch_nolld.cpp"
#include "ch_lld_staticlink.cpp"
```

exlbt/input/build-slinker.sh

```
#!/usr/bin/env bash

source functions.sh

sh_name=build-slinker.sh
argNum=$#
arg1=$1
```

```
arg2=$2

prologue;

clang -target mips-unknown-linux-gnu -c start.cpp -emit-llvm -o start.bc
clang -target mips-unknown-linux-gnu -c debug.cpp -emit-llvm -o debug.bc
clang -target mips-unknown-linux-gnu -c printf-stdarg-def.c -emit-llvm \
-o printf-stdarg-def.bc
clang -target mips-unknown-linux-gnu -c printf-stdarg.c -emit-llvm \
-o printf-stdarg.bc
clang -target mips-unknown-linux-gnu -c ${LBDEXDIR}/input/ch4_1_2.cpp -emit-llvm -o ch4_1_2.bc
clang -O1 -target mips-unknown-linux-gnu -c ${LBDEXDIR}/input/ch8_1_5.cpp -emit-llvm -o ch8_1_5.bc
clang -O1 -target mips-unknown-linux-gnu -c ${LBDEXDIR}/input/ch8_3.cpp -emit-llvm -o ch8_3.bc
clang -O1 -target mips-unknown-linux-gnu -c ${LBDEXDIR}/input/ch8_5.cpp -emit-llvm -o ch8_5.bc
clang -O1 -target mips-unknown-linux-gnu -c ${LBDEXDIR}/input/ch9_2_3_tailcall.cpp -emit-llvm -o \
ch9_2_3_tailcall.bc
clang -c ${LBDEXDIR}/input/ch9_4.cpp -emit-llvm -o ch9_4.bc
clang -I${LBDEXDIR}/input/ -target mips-unknown-linux-gnu -c ch_slinker.cpp -emit-llvm \
-o ch_slinker.bc
${TOOLDIR}/llc -march=cpu0${endian} -mcpu=${CPU} -relocation-model=static \
-filetype=obj start.bc -o start.cpu0.o
${TOOLDIR}/llc -march=cpu0${endian} -mcpu=${CPU} -relocation-model=static \
-filetype=obj debug.bc -o debug.cpu0.o
${TOOLDIR}/llc -march=cpu0${endian} -mcpu=${CPU} -relocation-model=static \
-filetype=obj printf-stdarg-def.bc -o printf-stdarg-def.cpu0.o
${TOOLDIR}/llc -march=cpu0${endian} -mcpu=${CPU} -relocation-model=static \
-filetype=obj printf-stdarg.bc -o printf-stdarg.cpu0.o
${TOOLDIR}/llc -march=cpu0${endian} -mcpu=${CPU} -relocation-model=static \
-filetype=obj -cpu0-enable-overflow=true ch4_1_2.bc -o ch4_1_2.cpu0.o
${TOOLDIR}/llc -march=cpu0${endian} -mcpu=${CPU} -relocation-model=static \
-filetype=obj ch8_1_5.bc -o ch8_1_5.cpu0.o
${TOOLDIR}/llc -march=cpu0${endian} -mcpu=${CPU} -relocation-model=static \
-filetype=obj ch8_3.bc -o ch8_3.cpu0.o
${TOOLDIR}/llc -march=cpu0${endian} -mcpu=${CPU} -relocation-model=static \
-filetype=obj ch8_5.bc -o ch8_5.cpu0.o
${TOOLDIR}/llc -march=cpu0${endian} -mcpu=${CPU} -relocation-model=static \
-filetype=obj -enable-cpu0-tail-calls ch9_2_3_tailcall.bc -o \
ch9_2_3_tailcall.cpu0.o
${TOOLDIR}/llc -march=cpu0${endian} -mcpu=${CPU} -relocation-model=static \
-filetype=obj ch9_4.bc -o ch9_4.cpu0.o
${TOOLDIR}/llc -march=cpu0${endian} -mcpu=${CPU} -relocation-model=static \
-filetype=obj ch_slinker.bc -o ch_slinker.cpu0.o
${TOOLDIR}/llc -march=cpu0${endian} -mcpu=${CPU} -relocation-model=static \
-filetype=obj lib_cpu0.ll -o lib_cpu0.o
${TOOLDIR}/lld -flavor gnu -target cpu0${endian}-unknown-linux-gnu start.cpu0.o \
debug.cpu0.o printf-stdarg-def.cpu0.o printf-stdarg.cpu0.o ch4_1_2.cpu0.o \
ch8_1_5.cpu0.o ch8_3.cpu0.o ch8_5.cpu0.o ch9_2_3_tailcall.cpu0.o ch9_4.cpu0.o \
ch_slinker.cpu0.o lib_cpu0.o -o a.out

epilogue;

1-160-136-173:input Jonathan$ pwd
/Users/Jonathan/test/lbt/exlbt/input
114-37-148-111:input Jonathan$ bash build-slinker.sh cpu032I le
...
In file included from ch_slinker.cpp:23:
./ch_lld_staticlink.cpp:8:15: warning: conversion from string literal to
'char *' is deprecated
```

```
      [-Wdeprecated-writable-strings]
  char *ptr = "Hello world!";
              ^
1 warning generated.
114-37-148-111:input Jonathan$ cd ../../lbdex/verilog/
114-37-148-111:verilog Jonathan$ ./cpu0IIs
WARNING: ./cpu0.v:369: $readmemh(cpu0.hex): Not enough words in the file for
the requested range [0:524287].
taskInterrupt(001)
74
253
3
1
14
3
-126
130
-32766
32770
393307
16777222
51
2
2147483647
-2147483648
7
15
test_nolld(): PASS
taskInterrupt(011)
Overflow exception
taskInterrupt(011)
Overflow exception
test_overflow = 0, PASS
global variable gI = 100, PASS
test_ctrl2(): a = 1, b = 0, c = 1, d = 0, PASS
select_1() = 1
select_2() = 1
select_3() = 1
test_select_global_pic() = 100, PASS
test_tailcall(5) = 120, PASS
date1 = 2012 10 12 1 2 3, PASS
date2 = 2012 10 12 1 2 3, PASS
time2 = 1 10 12, PASS
time3 = 1 10 12, PASS
date1 = 2013 1 26 12 21 10, PASS
date2 = 2013 1 26 12 21 10, PASS
test_template() = 15, PASS
test_alloc() = 31, PASS
test_inlineasm() = 53, PASS
20
10
5
test_cpp_polymorphism() = 0, PASS
taskInterrupt(011)
Software interrupt
taskInterrupt(011)
Harware interrupt 0
taskInterrupt(011)
```

```
Harware interrupt 1
total cpu cycles = 252660
RET to PC < 0, finished!
```

As above, by taking the open source code advantage, Cpu0 got the more stable printf() program. Once Cpu0 backend can translate the printf() function of the open source C printf() program into machine instructions, the llvm Cpu0 backend can be verified with printf(). With the quality code of open source printf() program, the Cpu0 toolchain is extended from compiler backend to C std library support. (Notice that some GPL open source code are not quality code, but some are.)

The "Overflow exception is printed twice meaning the ISR() of debug.cpp is called twice from ch4_1_2.cpp. The printed "taskInterrupt(001)" and "taskInterrupt(011)" just are trace message from cpu0.v code.

Cpu0 lld structure

The Cpu0LinkingContext include the context information for those input obj files and output execution file you want to link. When do linking, the following code will create Cpu0LinkingContext.

exlbt/lld/ELFLinkingContext.h

```
class ELFLinkingContext : public LinkingContext {
public:
  ...
  static std::unique_ptr<ELFLinkingContext> create(llvm::Triple);
  ...
}
```

exlbt/lld/ELFLinkingContext.cpp

```
std::unique_ptr<ELFLinkingContext>
ELFLinkingContext::create(llvm::Triple triple) {
  switch (triple.getArch()) {
  ...
  case llvm::Triple::cpu0:
    return std::unique_ptr<ELFLinkingContext>(
        new lld::elf::Cpu0LinkingContext(triple));
  default:
    return nullptr;
  }
}
```

While Cpu0LinkingContext is created by lld ELF driver as above, the following code in Cpu0LinkingContext constructor will create Cpu0TargetHandler and passing the Cpu0LinkingContext object pointer to Cpu0TargeHandler.

exlbt/lld/Cpu0/Cpu0LinkingContext.h

```
class Cpu0LinkingContext LLVM_FINAL : public ELFLinkingContext {
public:
  Cpu0LinkingContext(llvm::Triple triple)
      : ELFLinkingContext(triple, std::unique_ptr<TargetHandlerBase>(
                                  new Cpu0TargetHandler(*this))) {}
```

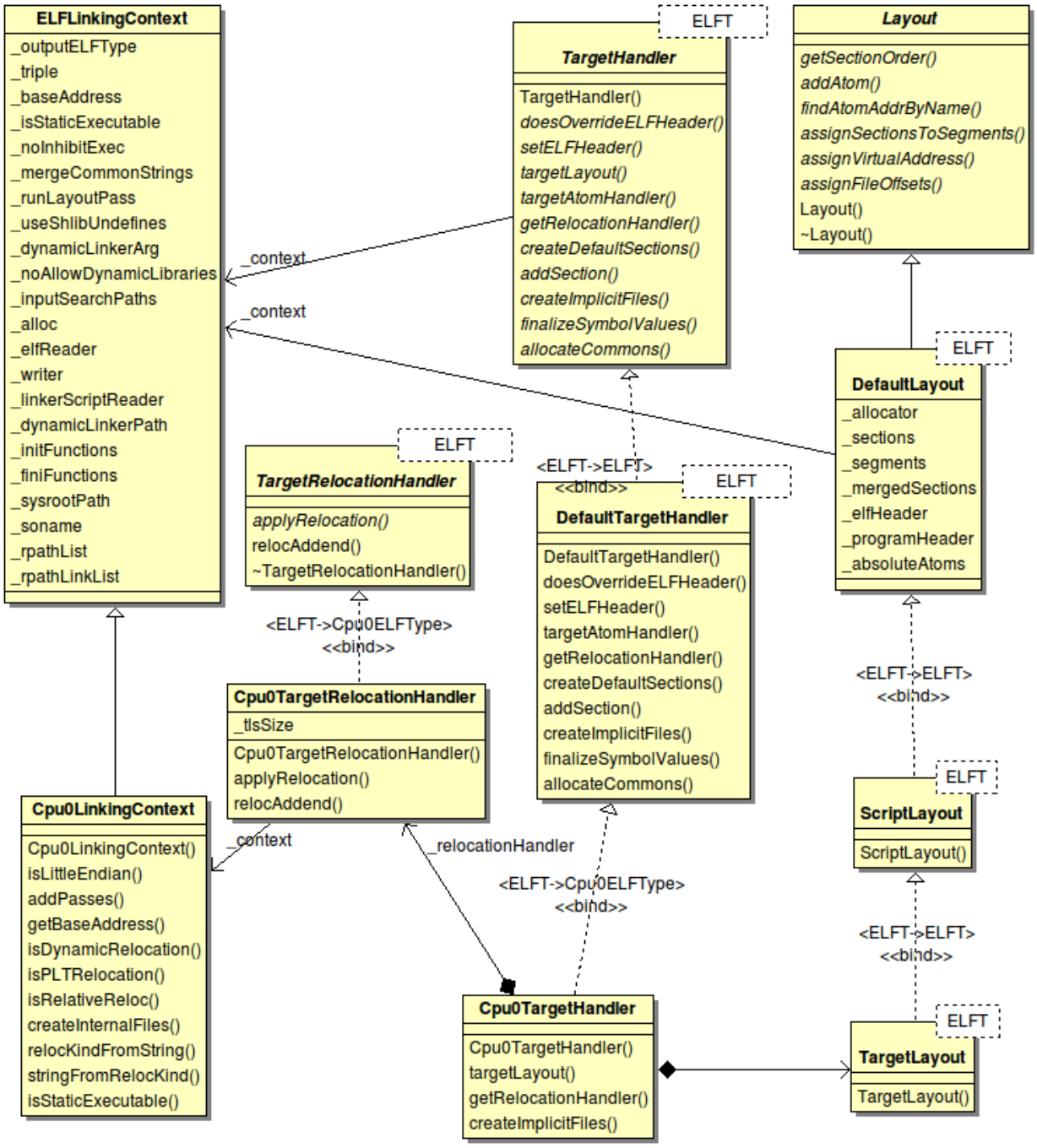

Figure 2.5: Cpu0 lld class relationship

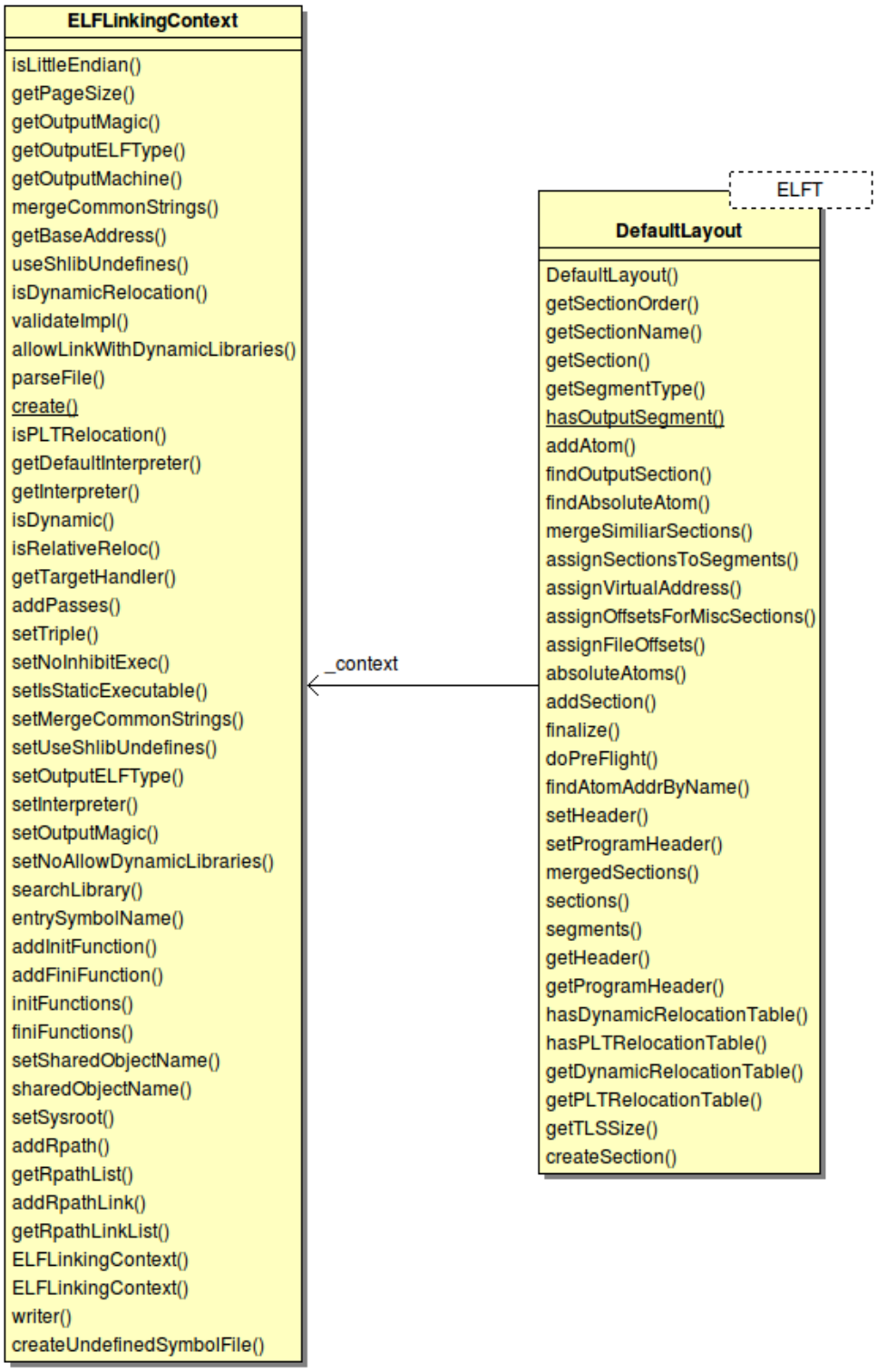

Figure 2.6: Cpu0 lld ELFLinkingContext and DefaultLayout member functions

```
  ...
}
```

Finally, the Cpu0TargeHandler constructor will create other related objects and set up the relation reference object pointers as Figure 2.5 depicted by the following code.

exlbt/lld/Cpu0/Cpu0TargetHandler.cpp

```
Cpu0TargetHandler::Cpu0TargetHandler(Cpu0LinkingContext &context)
    : DefaultTargetHandler(context), _gotFile(new GOTFile(context)),
      _relocationHandler(context), _targetLayout(context) {}
```

According chapter ELF, the linker stands for resolve the relocation records. The following code give the chance to let lld system call our relocation function at proper time.

exlbt/lld/Cpu0/Cpu0RelocationPass.cpp

```
std::unique_ptr<Pass>
lld::elf::createCpu0RelocationPass(const Cpu0LinkingContext &ctx) {
  switch (ctx.getOutputELFType()) {
  case llvm::ELF::ET_EXEC:
  // when the output file is execution file: e.g. a.out
#ifdef DLINKER
    if (ctx.isDynamic())
    // when the a.out refer to shared object *.so
      return std::unique_ptr<Pass>(new DynamicRelocationPass(ctx));
    else
#endif // DLINKER
      return std::unique_ptr<Pass>(new StaticRelocationPass(ctx));
#ifdef DLINKER
  case llvm::ELF::ET_DYN:
  // when the output file is shared object: e.g. foobar.so
    return std::unique_ptr<Pass>(new DynamicRelocationPass(ctx));
#endif // DLINKER
  case llvm::ELF::ET_REL:
    return std::unique_ptr<Pass>();
  default:
    llvm_unreachable("Unhandled output file type");
  }
}
```

The "#ifdef DLINKER" part is for dynamic linker which will be used in next section. For static linker, a StaticRelocationPass object is created and return.

Now the following code of Cpu0TargetRelocationHandler::applyRelocation() will be called through Cpu0TargetHandler by lld ELF driver when it meets each relocation record.

exlbt/lld/Cpu0/Cpu0RelocationHandler.cpp

```
ErrorOr<void> Cpu0TargetRelocationHandler::applyRelocation(
    ELFWriter &writer, llvm::FileOutputBuffer &buf, const lld::AtomLayout &atom,
    const Reference &ref) const {

  switch (ref.kind()) {
```

```
  case R_CPU0_NONE:
    break;
  case R_CPU0_HI16:
    relocHI16(location, relocVAddress, targetVAddress, ref.addend());
    break;
  case R_CPU0_LO16:
    relocLO16(location, relocVAddress, targetVAddress, ref.addend());
    break;
  ...
  }
  return error_code::success();
}
```

exlbt/lld/Cpu0/Cpu0TargetHandler.h

```
class Cpu0TargetHandler LLVM_FINAL
    : public DefaultTargetHandler<Cpu0ELFType> {
public:
  ..
  virtual const Cpu0TargetRelocationHandler &getRelocationHandler() const {
    return _relocationHandler;
  }
```

Summary as Figure 2.7.

Remind, static std::unique_ptr<ELFLinkingContext> ELFLinkingContext::create(llvm::Triple) is called without an object of class ELFLinkingContext instance (because the static keyword). The Cpu0LinkingContext constructor will create it's ELFLinkingContext part. The std::unique_ptr came from c++11 standard. The unique_ptr objects automatically delete the object they manage (using a deleter) as soon as themselves are destroyed. Just like the Singlelten pattern in Design Pattern book or Smart Pointers in Effective C++ book. [4]

As Figure 2.5 depicted, the Cpu0TargetHandler include the members or pointers which can access to other object. The way to access Cpu0TargetHandler object from Cpu0LinkingContext or Cpu0RelocationHandler rely on LinkingContext::getTargetHandler() function. As Figure 2.8 depicted, the unique_ptr point to Cpu0TargetHandler will be saved in LinkingContext contructor function.

List the c++11 unique_ptr::get() and move() which used in Figure 2.8 as follows.

Note: std::unique_ptr::get() [5]

pointer get() const noexcept;

Get pointer Returns the stored pointer.

Note: std::move() [6]

for example: std::string bar = "bar-string"; std::move(bar);

bar is null after std::move(bar);

---

[4] http://www.cplusplus.com/reference/memory/unique_ptr/
[5] http://www.cplusplus.com/reference/memory/unique_ptr/get/
[6] http://www.cplusplus.com/reference/utility/move/

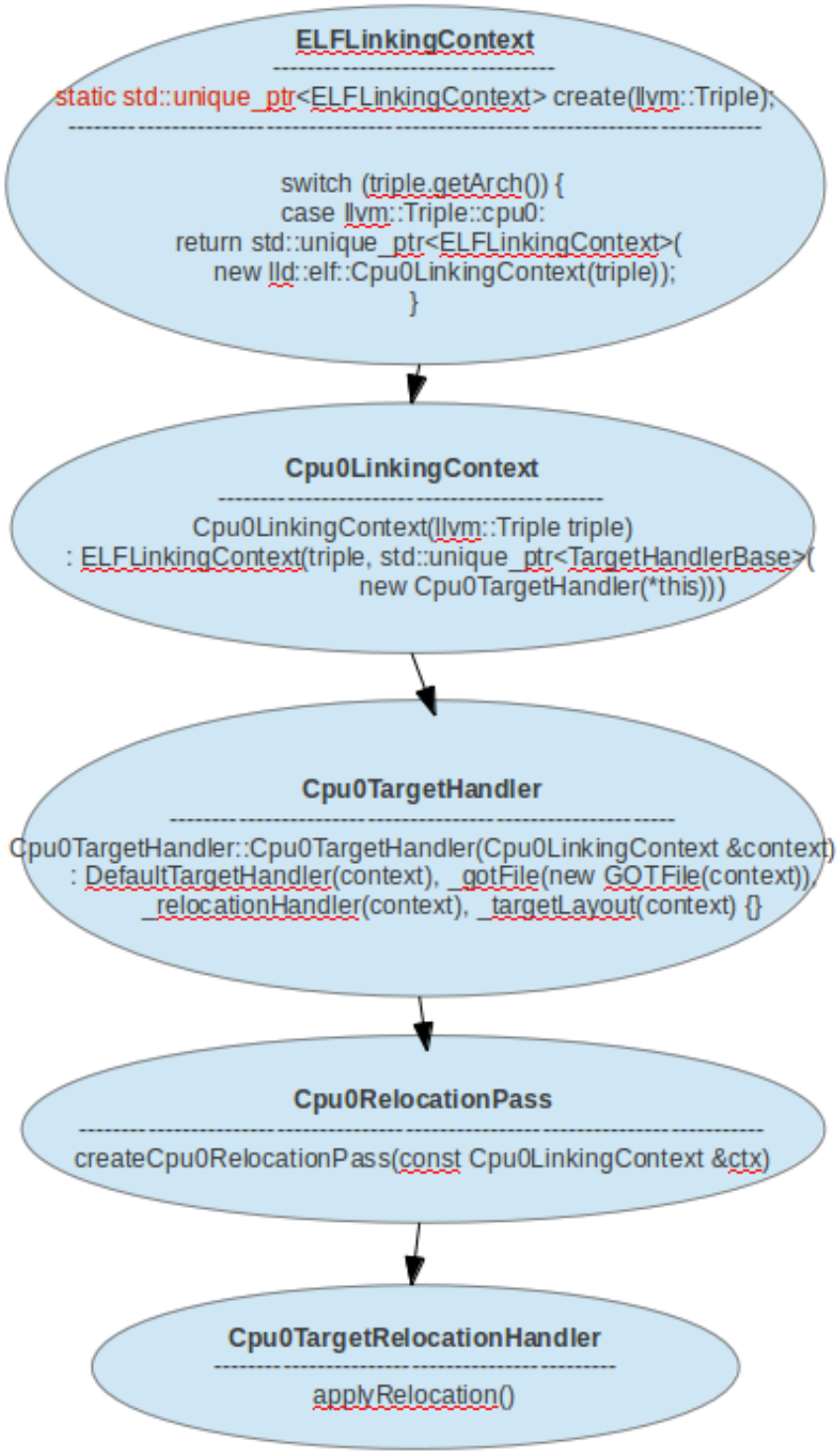

Figure 2.7: Cpu0 lld related objects created sequence

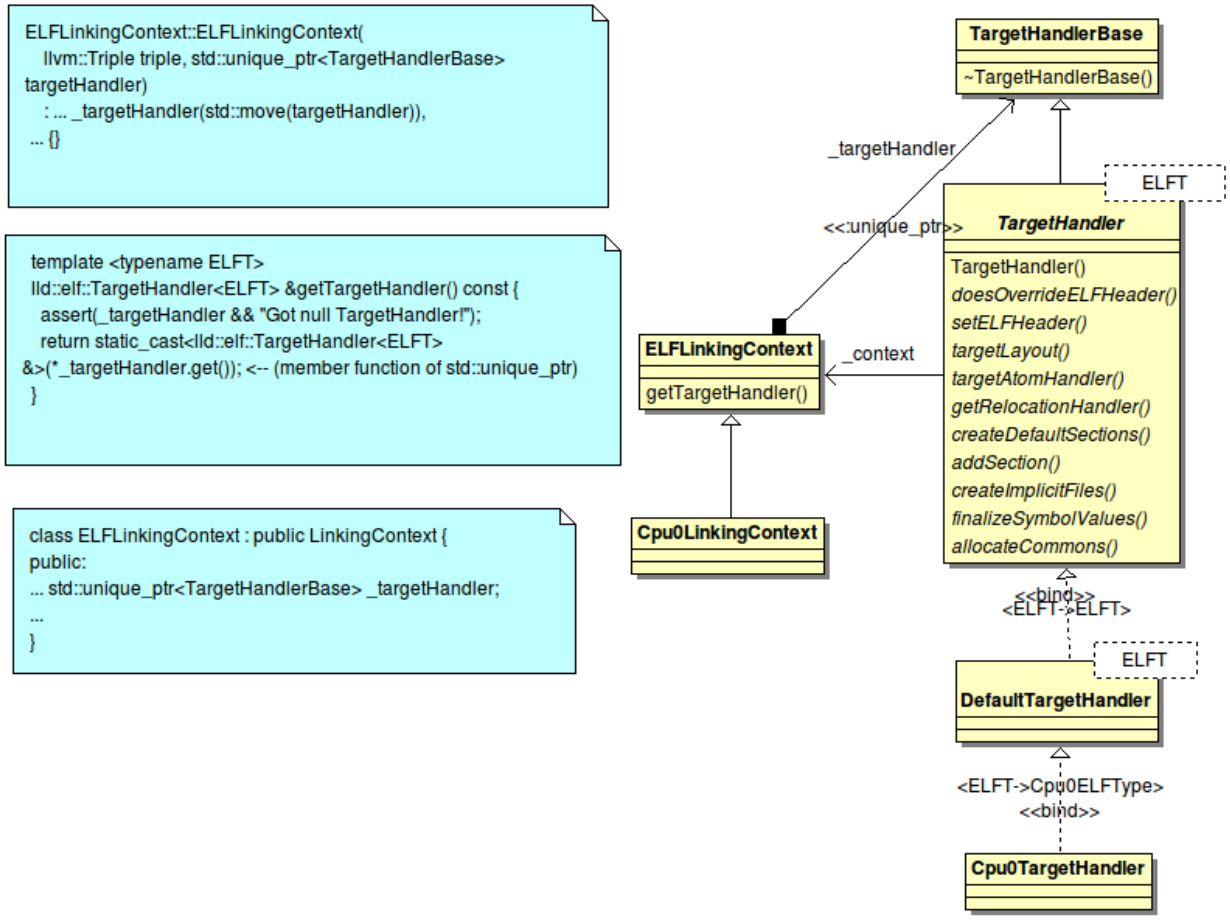

Figure 2.8: Cpu0LinkingContext get Cpu0TargetHandler through &getTargetHandler()

2.2.5 Dynamic linker

In addition to the lld code with #ifdef DLINKER. The following code in Verilog exists to support dynamic linker.

lbdex/verilog/dynlinker.v

```
`define DLINKER_INFO_ADDR  'h70000
`define GPADDR    'h7FFF0

`ifdef DLINKER
  task setDynLinkerInfo; begin
// below code set memory as follows,
//                                                      (4 bytes)
//                                                    ----------------------------------------
// DLINKER_INFO_ADDR ---------->                      | numDynEntry                          |
//                                                    ----------------------------------------
// DLINKER_INFO_ADDR+4 -------->                      | index of dynsym (0st row)            |
//   above is the 1st word of section .dynsym of libfoobar.cpu0.so.
// DLINKER_INFO_ADDR+8 -------->                      | index of dynsym (1st row)            |
//                                                    | ...                                  |
// DLINKER_INFO_ADDR+(numDynEntry-1)*4 --------------> | index of dynsym (the last row)       |
//                                                    ----------------------------------------
// DLINKER_INFO_ADDR+numDynEntry*4 ------------------> | 1st function (la()) offset in lib    |
// DLINKER_INFO_ADDR+numDynEntry*4+4 ----------------> | 1st function (la()) name (48 bytes)  |
//                                                    | ...                                  |
// DLINKER_INFO_ADDR+numDynEntry+(numDynEntry-1)*4 ---> | last function (bar()) offset in lib  |
// DLINKER_INFO_ADDR+numDynEntry+(numDynEntry-1)*4+4 -> | last function (bar()) name           |
//                                                    ----------------------------------------
// DLINKER_INFO_ADDR+4+numDynEntry*4+numDynEntry*52 --> | .dynstr of lib                       |
//                                                    |   ...                                |
//                                                    ----------------------------------------
  // caculate number of dynamic entries
    numDynEntry = 0;
    j = 0;
    for (i=0; i < 384 && j == 0; i=i+52) begin
       if (so_func_offset[i] == `MEMEMPTY && so_func_offset[i+1] == `MEMEMPTY &&
           so_func_offset[i+2] == `MEMEMPTY && so_func_offset[i+3] == `MEMEMPTY) begin
         numDynEntry = i/52;
         j = 1;
       `ifdef DEBUG_DLINKER
         $display("numDynEntry = %8x", numDynEntry);
       `endif
       end
    end
  // save number of dynamic entries to memory address `DLINKER_INFO_ADDR
    m[`DLINKER_INFO_ADDR] = numDynEntry[31:24];
    m[`DLINKER_INFO_ADDR+1] = numDynEntry[23:16];
    m[`DLINKER_INFO_ADDR+2] = numDynEntry[15:8];
    m[`DLINKER_INFO_ADDR+3] = numDynEntry[7:0];
  // copy section .dynsym of ELF to memory address `DLINKER_INFO_ADDR+4
    i = `DLINKER_INFO_ADDR+4;
    for (j=0; j < (4*numDynEntry); j=j+4) begin
      m[i] = dsym[j];
      m[i+1] = dsym[j+1];
      m[i+2] = dsym[j+2];
      m[i+3] = dsym[j+3];
      i = i + 4;
```

```
    end
  // copy the offset values of section .text of shared library .so of ELF to
  // memory address `DLINKER_INFO_ADDR+4+numDynEntry*4
    i = `DLINKER_INFO_ADDR+4+numDynEntry*4;
    l = 0;
    for (j=0; j < numDynEntry; j=j+1) begin
      for (k=0; k < 52; k=k+1) begin
        m[i] = so_func_offset[l];
        i = i + 1;
        l = l + 1;
      end
    end
  `ifdef DEBUG_DLINKER
    i = `DLINKER_INFO_ADDR+4+numDynEntry*4;
    for (j=0; j < (8*numDynEntry); j=j+8) begin
       $display("%8x: %8x", i, {m[i], m[i+1], m[i+2], m[i+3]});
      i = i + 8;
    end
  `endif
  // copy section .dynstr of ELF to memory address
  // `DLINKER_INFO_ADDR+4+numDynEntry*4+numDynEntry*52
    i=`DLINKER_INFO_ADDR+4+numDynEntry*4+numDynEntry*52;
    for (j=0; dstr[j] != `MEMEMPTY; j=j+1) begin
      m[i] = dstr[j];
      i = i + 1;
    end
  `ifdef DEBUG_DLINKER
    $display("In setDynLinkerInfo()");
    for (i=`DLINKER_INFO_ADDR; i < `MEMSIZE; i=i+4) begin
       if (m[i] != `MEMEMPTY || m[i+1] != `MEMEMPTY ||
         m[i+2] != `MEMEMPTY || m[i+3] != `MEMEMPTY)
         $display("%8x: %8x", i, {m[i], m[i+1], m[i+2], m[i+3]});
    end
    $display("global address %8x", {m[`GPADDR], m[`GPADDR+1],
             m[`GPADDR+2], m[`GPADDR+3]});
    $display("gp = %8x", gp);
  `endif
// below code set memory as follows,
//                                  ------------------------------------
// gp ------------------------------> | all 0                              | (16 bytes)
// gp+16 ---------------------------> | 0                            |
// gp+16+1*4 -----------------------> | 1st plt entry address      | (4 bytes)
//                                  | ...                          |
// gp+16+(numDynEntry-1)*4 ---------> | the last plt entry address |
//                                  ------------------------------------
// gpPlt ---------------------------> | all 0                              | (16 bytes)
// gpPlt+16+0*8'h10 ----------------> | 32'h10: pointer to plt0            |
// gpPlt+16+1*8'h10 ----------------> | 1st plt entry                      |
// gpPlt+16+2*8'h10 ----------------> | 2nd plt entry                      |
//                                  | ...                                |
// gpPlt+16+(numDynEntry-1)*8'h10 --> | the last plt entry                 |
//                                  ------------------------------------
// note: gp point to the _GLOBAL_OFFSET_TABLE_,
//       numDynEntry = actual number of functions + 1.
//   gp+1*4..gp+numDynEntry*4 set to 8'h10 plt0 which will jump to dynamic
//   linker.
//   After dynamic linker load function to memory, it will set gp+index*4 to
//   function memory address. For example, if the function index is 2, then the
```

```
//   gp+2*4 is set to the memory address of this loaded function.
//   Then the the caller call
//   "ld $t9, 2*4($gp)" and "ret $t9" will jump to this loaded function directly.

    gpPlt = gp+16+numDynEntry*4;
    // set (gpPlt-16..gpPlt-1) to 0
    for (j=16; j >= 1; j=j-1)
      m[gpPlt+j] = 8'h00;
    // put plt in (gpPlt..gpPlt+numDynEntry*8'h10+1)
    for (i=1; i < numDynEntry; i=i+1) begin
      // (gp+'8h10..gp+numDynEntry*'8h10+15) set to plt entry
      // addiu        $t9, $zero, dynsym_idx
      m[gpPlt+i*8'h10] = 8'h09;
      m[gpPlt+i*8'h10+1] = 8'h60;
      m[gpPlt+i*8'h10+2] = i[15:8];
      m[gpPlt+i*8'h10+3] = i[7:0];
      // st         $t9, 0($gp)
      m[gpPlt+i*8'h10+4] = 8'h02;
      m[gpPlt+i*8'h10+5] = 8'h6b;
      m[gpPlt+i*8'h10+6] = 0;
      m[gpPlt+i*8'h10+7] = 0;
      // ld         $t9, ('16h0010)($gp)
      m[gpPlt+i*8'h10+8] = 8'h01;
      m[gpPlt+i*8'h10+9] = 8'h6b;
      m[gpPlt+i*8'h10+10] = 0;
      m[gpPlt+i*8'h10+11] = 8'h10;
      // ret         $t9
      m[gpPlt+i*8'h10+12] = 8'h3c;
      m[gpPlt+i*8'h10+13] = 8'h60;
      m[gpPlt+i*8'h10+14] = 0;
      m[gpPlt+i*8'h10+15] = 0;
    end

  // .got.plt offset(0x00.0x03) has been set to 0 in elf already.
  // Set .got.plt offset(8'h10..numDynEntry*'8h10) point to plt entry as above.
  `ifdef DEBUG_DLINKER
        $display("numDynEntry = %8x", numDynEntry);
  `endif
//      j32=32'h1fc0; // m[32'h1fc]="something" will hang. Very tricky
    m[gp+16] = 8'h0;
    m[gp+16+1] = 8'h0;
    i=pltAddr[0]+16;
    m[gp+16+2] = i[15:8];   // .plt section addr + 16
    m[gp+16+3] = i[7:0];

    j32=gpPlt+16;
    for (i=1; i < numDynEntry; i=i+1) begin
      m[gp+16+i*4] = j32[31:24];
      m[gp+16+i*4+1] = j32[23:16];
      m[gp+16+i*4+2] = j32[15:8];
      m[gp+16+i*4+3] = j32[7:0];
      j32=j32+16;
    end
  `ifdef DEBUG_DLINKER
    // show (gp..gp+numDynEntry*4-1)
    for (i=0; i < numDynEntry; i=i+1) begin
      $display("%8x: %8x", gp+16+i*4, {m[gp+16+i*4], m[gp+16+i*4+1],
               m[gp+16+i*4+2], m[gp+16+i*4+3]});
```

```
    end
    // show (gpPlt..gpPlt+(numDynEntry+1)*8'h10-1)
    for (i=0; i < numDynEntry; i=i+1) begin
      for (j=0; j < 16; j=j+4)
        $display("%8x: %8x", gpPlt+i*8'h10+j,
                 {m[gpPlt+i*8'h10+j],
                  m[gpPlt+i*8'h10+j+1],
                  m[gpPlt+i*8'h10+j+2],
                  m[gpPlt+i*8'h10+j+3]});
    end
  `endif
  end endtask
`endif

`ifdef DLINKER
  task loadToFlash; begin
  // erase memory
    for (i=0; i < `MEMSIZE; i=i+1) begin
       flash[i] = `MEMEMPTY;
    end
    $readmemh("dlconfig/libso.hex", flash);
  `ifdef DEBUG_DLINKER
    for (i=0; i < `MEMSIZE && (flash[i] != `MEMEMPTY ||
         flash[i+1] != `MEMEMPTY || flash[i+2] != `MEMEMPTY ||
         flash[i+3] != `MEMEMPTY); i=i+4) begin
       $display("%8x: %8x", i, {flash[i], flash[i+1], flash[i+2], flash[i+3]});
    end
  `endif
  end endtask
`endif

`ifdef DLINKER
  task createDynInfo; begin
    $readmemh("dlconfig/global_offset", globalAddr);
    m[`GPADDR]   = globalAddr[0];
    m[`GPADDR+1] = globalAddr[1];
    m[`GPADDR+2] = globalAddr[2];
    m[`GPADDR+3] = globalAddr[3];
    gp[31:24] = globalAddr[0];
    gp[23:16] = globalAddr[1];
    gp[15:8] = globalAddr[2];
    gp[7:0] = globalAddr[3];
    $readmemh("dlconfig/plt_offset", pltAddr);
  `ifdef DEBUG_DLINKER
    $display("global address %8x", {m[`GPADDR], m[`GPADDR+1],
             m[`GPADDR+2], m[`GPADDR+3]});
    $display("gp = %8x", gp);
    $display("pltAddr = %8x", pltAddr[0]);
  `endif
`endif
`ifdef DLINKER
    for (i=0; i < 192; i=i+1) begin
       dsym[i] = `MEMEMPTY;
    end
    for (i=0; i < 96; i=i+1) begin
       dstr[i] = `MEMEMPTY;
    end
    for (i=0; i <384; i=i+1) begin
```

```
        so_func_offset[i] = `MEMEMPTY;
    end
    $readmemh("dlconfig/dynsym", dsym);
    $readmemh("dlconfig/dynstr", dstr);
    $readmemh("dlconfig/so_func_offset", so_func_offset);
    setDynLinkerInfo();
  end endtask
`endif
```

lbdex/verilog/flashio.v

```
`define FLASHADDR 'hA0000

`ifdef DLINKER
    end else if (abus >= `FLASHADDR && abus <= `FLASHADDR+`MEMSIZE-4) begin
      fabus = abus-`FLASHADDR;
      if (en == 1 && rw == 0) begin // r_w==0:write
        data = dbus_in;
        case (m_size)
        `BYTE:  {flash[fabus]} = dbus_in[7:0];
        `INT16: {flash[fabus], flash[fabus+1] } = dbus_in[15:0];
        `INT24: {flash[fabus], flash[fabus+1], flash[fabus+2]} = dbus_in[24:0];
        `INT32: {flash[fabus], flash[fabus+1], flash[fabus+2], flash[fabus+3]}
                = dbus_in;
        endcase
      end else if (en == 1 && rw == 1) begin// r_w==1:read
        case (m_size)
        `BYTE:  data = {8'h00  , 8'h00,   8'h00,   flash[fabus]};
        `INT16: data = {8'h00  , 8'h00,   flash[fabus], flash[fabus+1]};
        `INT24: data = {8'h00  , flash[fabus], flash[fabus+1], flash[fabus+2]};
        `INT32: data = {flash[fabus], flash[fabus+1], flash[fabus+2],
                        flash[fabus+3]};
        endcase
      end else
        data = 32'hZZZZZZZZ;
`endif
```

lbdex/verilog/cpu0ld.v

```
`define DLINKER  // Dynamic Linker Support
//`define DEBUG_DLINKER   // Dynamic Linker Debug
// TRACE: Display the memory contents of the loaded program and data
//`define TRACE

`include "cpu0.v"
```

lbdex/verilog/cpu0lld.v

```
`define CPU0II
`define DLINKER  // Dynamic Linker Support
//`define DEBUG_DLINKER   // Dynamic Linker Debug
// TRACE: Display the memory contents of the loaded program and data
//`define TRACE
```

```
`include "cpu0.v"
```

The following code ch_dynamiclinker.cpp and foobar.cpp is the example for dynamic linker demostration. File dynamic_linker.cpp is what our implementaion to execute the dynamic linker function on Cpu0 Verilog machine.

exlbt/input/debug.h

```
#ifndef _DEBUG_H_
#define _DEBUG_H_

#define STOP \
  asm("lui $t9, 0xffff"); \
  asm("addiu $t9, $zero, 0xffff"); \
  asm("ret $t9");

#define ENABLE_TRACE \
  asm("ori $sw, $sw, 0x0020");

#define DISABLE_TRACE \
  asm("lui $at, 0xffff");       \
  asm("ori $at, $at, 0xffdf");  \
  asm("and $sw, $sw, $at"); // clear `D

#define SET_OVERFLOW \
  asm("ori $sw, $sw, 0x008");

#define CLEAR_OVERFLOW \
  asm("lui $7, 0xffff");        \
  asm("ori $7, $7, 0xfff7");    \
  asm("and $sw, $sw, $7"); // clear `V

#define SET_SOFTWARE_INT \
  asm("ori $sw, $sw, 0x4000");

#define CLEAR_SOFTWARE_INT \
  asm("lui $7, 0xffff");        \
  asm("ori $7, $7, 0xbfff");    \
  asm("and $sw, $sw, $7");

#define SAVE_REGISTERS          \
  asm("lui $at, 7");            \
  asm("ori $at, $at, 0xff00");  \
  asm("st $2,   0($at)");       \
  asm("st $3,   4($at)");       \
  asm("st $4,   8($at)");       \
  asm("st $5,  12($at)");       \
  asm("st $t9, 16($at)");       \
  asm("st $7,  20($at)");       \
  asm("st $8,  24($at)");       \
  asm("st $9,  28($at)");       \
  asm("st $10, 32($at)");       \
  asm("st $gp, 36($at)");       \
  asm("st $12, 40($at)");       \
  asm("st $13, 44($at)");

#define RESTORE_REGISTERS       \
```

```
  asm("lui $at,  7");           \
  asm("ori $at,  $at, 0xff00"); \
  asm("ld  $2,   0($at)");      \
  asm("ld  $3,   4($at)");      \
  asm("ld  $4,   8($at)");      \
  asm("ld  $5,  12($at)");      \
  asm("ld  $t9, 16($at)");      \
  asm("ld  $7,  20($at)");      \
  asm("ld  $8,  24($at)");      \
  asm("ld  $9,  28($at)");      \
  asm("ld  $10, 32($at)");      \
  asm("ld  $gp, 36($at)");      \
  asm("ld  $12, 40($at)");      \
  asm("ld  $13, 44($at)");

#define OVERFLOW     0x8
#define INT          0x2000
#define SOFTWARE_INT 0x4000
#define INT1         0x8000
#define INT2         0x10000

extern void int_sim();

#endif
```

exlbt/input/dynamic_linker.h

```
#ifndef _DYNAMIC_LINKER_H_
#define _DYNAMIC_LINKER_H_

#define DYNLINKER_INFO_ADDR  0x70000
#define DYNENT_SIZE          4
#define DYNPROGSTART         0x40000
#define FLASHADDR            0xA0000
#define GPADDR               0x7FFF0

#include "debug.h"

struct ProgAddr {
  int memAddr;
  int size;
};

extern void dynamic_linker_init();
extern void dynamic_linker();

#endif
```

exlbt/input/dynamic_linker.cpp

```
#include "dynamic_linker.h"

//#define DEBUG_DLINKER
#define PLT0ADDR 0x10
#define REGADDR  0x7ff00
```

```
extern "C" int printf(const char *format, ...);

int got_plt_fill[0x80] = {
1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1,
1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1,
1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1,
1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1,
1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1,
1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1,
1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1,
1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1
};

int progCounter = 0; // program counter, init to 0 in main()

ProgAddr prog[10];

void dynamic_linker()
{
  SAVE_REGISTERS;
//  static ProgAddr prog[10]; // has side effect (ProgAddr cannot be written in
// Virtual Box on iMac).
  int i = 0;
  int nextFreeAddr;
  int *src, *dest, *end;
  int numDynEntry = 0;
  int dynsym_idx = 0;
  int dynsym = 0;
  char *dynstr = 0;
  int libOffset = 0;
  int nextFunLibOffset = 0;
  volatile int memAddr = 0;
  numDynEntry = *((int*)(DYNLINKER_INFO_ADDR));
  int gp = *(int*)GPADDR;
#ifdef DEBUG_DLINKER
  printf("gp = %d\n", gp);
#endif
  dynsym_idx = *(int*)gp;
#ifdef DEBUG_DLINKER
  printf("numDynEntry = %d, dynsym_idx = %d\n", numDynEntry, dynsym_idx);
#endif
  dynsym = *(int*)((DYNLINKER_INFO_ADDR+4)+(dynsym_idx*DYNENT_SIZE));
  dynstr = (char*)(DYNLINKER_INFO_ADDR+4+numDynEntry*4+numDynEntry*52+dynsym);
  libOffset = *((int*)(DYNLINKER_INFO_ADDR+4+numDynEntry*4+(dynsym_idx-1)*52));
  for (i = dynsym_idx; i < numDynEntry; i++) {
    nextFunLibOffset = *((int*)(DYNLINKER_INFO_ADDR+4+numDynEntry*4+i*52));
    if (libOffset != nextFunLibOffset)
      break;
  }
#ifdef DEBUG_DLINKER
  printf("address of dstr = %x, dynsym = %d, dstr = %s\n",
         (int)dynstr, dynsym, dynstr);
  printf("libOffset = %d, nextFunLibOffset = %d, progCounter = %d\n",
         libOffset, nextFunLibOffset, progCounter);
#endif
  if (progCounter == 0)
     nextFreeAddr = DYNPROGSTART;
  else
```

```
    nextFreeAddr = prog[progCounter-1].memAddr+prog[progCounter-1].size;
  prog[progCounter].memAddr = nextFreeAddr;
  prog[progCounter].size = (nextFunLibOffset - libOffset);

#ifdef DEBUG_DLINKER
  printf("prog[progCounter].memAddr = %d, prog[progCounter].size = %d\n",
         prog[progCounter].memAddr, (unsigned int)(prog[progCounter].size));
#endif
  // Load program from (FLASHADDR+libOffset..FLASHADDR+nextFunLibOffset-1) to
  // (nextFreeAddr..nextFreeAddr+prog[progCounter].size-1)
  src = (int*)(FLASHADDR+libOffset);
  end = (int*)(src+prog[progCounter].size/4);
#ifdef DEBUG_DLINKER
  printf("end = %x, src = %x, nextFreeAddr = %x\n",
         (unsigned int)end, (unsigned int)src, (unsigned int)nextFreeAddr);
  printf("*src = %x\n", (unsigned int)(*src));
#endif
  printf("loading %s...\n", dynstr);
  for (dest = (int*)(prog[progCounter].memAddr); src < end; src++, dest++) {
    *dest = *src;
#ifdef DEBUG_DLINKER
    printf("*dest = %08x\n", (unsigned int)(*dest));
#endif
  }
  progCounter++;

#ifdef DEBUG_DLINKER
  printf("progCounter-1 = %x, prog[progCounter-1].memAddr = %x, \
         *prog[progCounter-1].memAddr = %x\n",
         (unsigned int)(progCounter-1), (unsigned int)(prog[progCounter-1].memAddr),
         *(unsigned int*)(prog[progCounter-1].memAddr));
#endif
  // Change .got.plt for "ld        $t9, idx($gp)"
  *((int*)(gp+0x10+dynsym_idx*0x04)) = prog[progCounter-1].memAddr;
  *(int*)(0x7FFE0) = prog[progCounter-1].memAddr;
#ifdef DEBUG_DLINKER
  printf("*((int*)(gp+0x10+dynsym_idx*0x10)) = %x, *(int*)(0x7FFE0) = %x\n",
         *((int*)(gp+0x10+dynsym_idx*0x10)), (unsigned int)(*(int*)(0x7FFE0)));
  printf("*((int*)(gp+0x04)) = %x, *((int*)(gp+0x08)) = %x, *((int*)(gp+0x0c)) = %x\n",
         *((int*)(gp+0x04)), *((int*)(gp+0x08)), *((int*)(gp+0x0c)));
#endif
  printf("run %s...\n", dynstr);
  RESTORE_REGISTERS;

  // restore $lr. The next instruction of foo() of main.cpp for the main.cpp
  // call foo() first time example.
  // The $lr, $fp and $sp saved in cpu0Plt0AtomContent of Cpu0LinkingContext.cpp.
  asm("ld $lr, 4($gp)"); // restore $lr
#ifdef DEBUG_DLINKER
  ENABLE_TRACE;
#endif
  asm("ld $fp, 8($gp)"); // restore $fp
  asm("ld $sp, 12($gp)"); // restore $sp
#ifdef DEBUG_DLINKER
  DISABLE_TRACE;
#endif
  // jmp to the dynamic linked function. It's foo() for the
  // caller, ch_dynamic_linker.cpp, call foo()
```

```
  // first time example.
  asm("lui $t9, 0x7");
  asm("ori $t9, $t9, 0xFFE0");
  asm("ld $t9, 0($t9)");
  asm("ret $t9");

  return;
}
```

exlbt/input/ch_dynamiclinker.cpp

```
#include "dynamic_linker.h"
#include "print.h"

extern "C" int printf(const char *format, ...);

extern int la(int x1, int x2);
extern int foo(int x1, int x2);
extern int bar();

int main()
{
//  ENABLE_TRACE;
  int a = 0;

#if 1
  a = foo(1, 2);
  printf("foo(1, 2) = %d\n", a);
#endif
#if 1
  a = bar();
  printf("bar() = %d\n", a);
#endif
#if 0
  a = foo(1, 2);
  printf("foo(1, 2) = %d\n", a);
#endif

  return 0;
}
```

exlbt/input/foobar.cpp

```
#include "dynamic_linker.h"

int la(int x1, int x2)
{
  int sum = x1 + x1 + x2;

  return sum;
}

int foo(int x1, int x2)
{
  int sum = x1 + x2;
```

```
  return sum;
}

#if 0
int factorial(int x)
{
  if (x > 0)
    return x*factorial(x-1);
  else
    return 1;
}
#endif

int bar()
{
  int a;
//  ENABLE_TRACE;
  a = foo(2, 2);
  a += la(2, 3); // 4+7=11
//  a += factorial(4); // 11+24=35

  return a;
}
```

exlbt/input/build-dlinker.sh

```
#!/usr/bin/env bash

source functions.sh

sh_name=build-dlinker.sh
argNum=$#
arg1=$1
arg2=

prologue;

rm -rf dlconfig
mkdir dlconfig

clang -target mips-unknown-linux-gnu -c start.cpp -emit-llvm -o start.bc
clang -target mips-unknown-linux-gnu -c debug.cpp -emit-llvm -o debug.bc
clang -target mips-unknown-linux-gnu -c dynamic_linker.cpp -emit-llvm \
-o dynamic_linker.cpu0.bc
clang -target mips-unknown-linux-gnu -c printf-stdarg-def.c -emit-llvm \
-o printf-stdarg-def.bc
clang -target mips-unknown-linux-gnu -c printf-stdarg.c -emit-llvm \
-o printf-stdarg.bc
clang -target mips-unknown-linux-gnu -c foobar.cpp -emit-llvm -o foobar.cpu0.bc
${TOOLDIR}/llc -march=cpu0 -mcpu=${CPU} -relocation-model=static -filetype=obj \
-cpu0-reserve-gp=true dynamic_linker.cpu0.bc -o dynamic_linker.cpu0.o
${TOOLDIR}/llc -march=cpu0 -mcpu=${CPU} -relocation-model=static -filetype=obj \
printf-stdarg-def.bc -o printf-stdarg-def.cpu0.o
${TOOLDIR}/llc -march=cpu0 -mcpu=${CPU} -relocation-model=static -filetype=obj \
-cpu0-reserve-gp=true printf-stdarg.bc -o printf-stdarg.cpu0.o
${TOOLDIR}/llc -march=cpu0 -mcpu=${CPU} -relocation-model=pic -filetype=obj \
```

```
-cpu0-reserve-gp=true -cpu0-no-cpload=true foobar.cpu0.bc -o foobar.cpu0.o
${TOOLDIR}/llc -march=cpu0 -mcpu=${CPU} -relocation-model=static -filetype=obj \
lib_cpu0.ll -o lib_cpu0.o
${TOOLDIR}/lld -flavor gnu -target cpu0-unknown-linux-gnu -shared -o \
libfoobar.cpu0.so foobar.cpu0.o
${TOOLDIR}/llc -march=cpu0 -mcpu=${CPU} -relocation-model=static -filetype=obj \
-cpu0-reserve-gp=true start.bc -o start.cpu0.o
${TOOLDIR}/llc -march=cpu0 -mcpu=${CPU} -relocation-model=static \
-filetype=obj debug.bc -o debug.cpu0.o
clang -target mips-unknown-linux-gnu -c ch_dynamiclinker.cpp -emit-llvm \
-o ch_dynamiclinker.cpu0.bc
${TOOLDIR}/llc -march=cpu0 -mcpu=${CPU} -relocation-model=static -filetype=obj \
-cpu0-reserve-gp=true ch_dynamiclinker.cpu0.bc -o ch_dynamiclinker.cpu0.o
${TOOLDIR}/lld -flavor gnu -target cpu0-unknown-linux-gnu start.cpu0.o \
printf-stdarg-def.cpu0.o printf-stdarg.cpu0.o dynamic_linker.cpu0.o \
ch_dynamiclinker.cpu0.o libfoobar.cpu0.so lib_cpu0.o debug.cpu0.o
${TOOLDIR}/llvm-objdump -elf2hex -le=false -cpu0dumpso libfoobar.cpu0.so \
> dlconfig/libso.hex
${TOOLDIR}/llvm-objdump -elf2hex -le=false -cpu0linkso a.out > cpu0.hex
cp -rf dlconfig cpu0.hex ../../lbdex/verilog/.
echo "0   /* 0: big endian, 1: little endian */" > ../../lbdex/verilog/cpu0.config
cat ../../lbdex/verilog/cpu0.config
```

Run

```
1-160-136-173 input Jonathan$ pwd
/Users/Jonathan/test/lbt/exlbt/input
1-160-136-173:input Jonathan$ bash build-dlinker.sh cpu032II
1-160-136-173:input Jonathan$ cd ../../lbdex/verilog/
1-160-136-173:verilog Jonathan$ pwd
/Users/Jonathan/test/lbt/lbdex/verilog
1-160-136-173:verilog Jonathan$ iverilog -o cpu0IId cpu0IId.v
1-160-136-173:verilog Jonathan$ ls
clean.sh  cpu0IId  cpu0Id.v  cpu0IId.v  cpu0IIs.v  cpu0Is.v  cpu0.v  dynlinker.v
flashio.v
1-160-136-173:verilog Jonathan$ ./cpu0IId
WARNING: ./cpu0.v:371: $readmemh(cpu0.hex): Not enough words in the file for
the requested range [0:524287].
WARNING: ./dynlinker.v:185: $readmemh(libso.hex): Not enough words in the
file for the requested range [0:524287].
WARNING: ./dynlinker.v:223: $readmemh(dynsym): Not enough words in the file
for the requested range [0:191].
WARNING: ./dynlinker.v:224: $readmemh(dynstr): Not enough words in the file
for the requested range [0:95].
WARNING: ./dynlinker.v:225: $readmemh(so_func_offset): Not enough words in
the file for the requested range [0:383].
numDynEntry = 00000005
taskInterrupt(001)
loading _Z3fooii...
run _Z3fooii...
foo(1, 2) = 3
loading _Z3barv...
run _Z3barv...
loading _Z2laii...
run _Z2laii...
bar() = 11
total cpu cycles = 50530
```

```
RET to PC < 0, finished!
```

The "#ifdef DEBUG_DLINKER" part of code in dynamic_linker.cpp is for debugging purpose (since we coding it and take time to debug). After skip these debug code, the dynamic_linker.cpp is short and not difficult to read.

The run result is under expectation. The main() call foo() function first. Function foo() is loaded by dynamic linker (dynamic_linker.cpp) from flash address FLASHADDR (defined in dynamic_linker.h) to memory. The flashio.v implement the simulation read from flash address. After loaded foo() body from flash, dynamic_linker.cpp jump to this loaded address by "ret $t9" instruction.

Same as static linker, you can generate slt instruction instead of cmp by change from cpu=cpu0I to cpu0=cpu0II in build-dlinker.sh and run it again to get the same result. Finally, since the dynamic linker is a demo implemenation, it supports big endian only.

How to work

After run build-dlinker.sh, the following files are created.

lbdex/verilog/cpu0.hex

```
/*Disassembly of section .plt:*/
/*.PLT0:*/
/*       0:*/ 36 00 00 3c                                    /* jmp     60*/
/*       4:*/ 36 00 00 04                                    /* jmp     4*/
/*       8:*/ 36 00 00 04                                    /* jmp     4*/
/*       c:*/ 36 ff ff fc                                    /* jmp     -4*/

/*.PLT0:*/
/*      10:*/ 02 eb 00 04                                    /* st      $lr, 4($gp)*/
/*      14:*/ 02 cb 00 08                                    /* st      $fp, 8($gp)*/
/*      18:*/ 02 db 00 0c                                    /* st      $sp, 12($gp)*/
/*      1c:*/ 36 00 09 b8                                    /* jmp     2488*/

/*__plt__Z3barv:*/
/*      20:*/ 01 6b 00 24                                    /* ld      $t9, 36($gp)
/*      24:*/ 3c 60 00 00                                    /* ret     $t9*/
/*      28:*/ 00 00 00 00                                    /* nop*/
/*      2c:*/ 00 00 00 00                                    /* nop*/

/*__plt__Z3fooii:*/
/*      30:*/ 01 6b 00 1c                                    /* ld      $t9, 28($gp)
/*      34:*/ 3c 60 00 00                                    /* ret     $t9*/
/*      38:*/ 00 00 00 00                                    /* nop*/
/*      3c:*/ 00 00 00 00                                    /* nop*/
...

/*main:*/
...
/*     d68:*/ 3b ff f2 b4                                    /* jsub    16773812*/ // call foo()
...
/*     d80:*/ 3b ff f3 28                                    /* jsub    16773928*/ // call printf()
/*     d84:*/ 3b ff f2 a8                                    /* jsub    16773800*/ // call bar()
...
/*     d9c:*/ 3b ff f3 0c                                    /* jsub    16773900*/ // call printf()
...
/*     db8:*/ 3c e0 00 00                                    /* ret     $lr*/
```

```
...
/*Contents of section .data:*/
/*20a8 */00 00 00 01  00 00 00 01  00 00 00 01  00 00 00 01 /*  ................*/
...
```

lbdex/verilog/dynstr

```
00 5f 5f 74 6c 73 5f 67 65 74 5f 61 64 64 72 00 5f 5a 32 6c 61 69 69 00 5f 5a
35 70 6f 77 65 72 69 00 5f 5a 33 66 6f 6f 69 69 00 5f 5a 33 62 61 72 76 00 5f
47 4c 4f 42 41 4c 5f 4f 46 46 53 45 54 5f 54 41 42 4c 45 5f 00 5f 44 59 4e 41
4d 49 43 00
```

exlbt/verilog/dynsym

```
00 00 00 00 00 00 00 01 00 00 00 10 00 00 00 18 00 00 00 22 00 00 00 2b 00 00
00 33 00 00 00 49
```

lbdex/verilog/global_offset

```
00 00 20 68
```

exlbt/input/num_dyn_entry

```
6
```

exlbt/input/libfoobar.cpu0.so

```
1-160-136-173:input Jonathan$ ~/llvm/test/cmake_debug_build/Debug/bin/
llvm-objdump -s libfoobar.cpu0.so

libfoobar.cpu0.so:    file format ELF32-CPU0

Contents of section :
...
Contents of section .dynsym:
 00e4 00000000 00000000 00000000 00000000  ................
 00f4 00000001 0000019c 00000000 12000004  ................
 0104 00000010 0000019c 0000003c 12000004  ...........<....
 0114 00000018 000001d8 00000038 12000004  ...........8....
 0124 00000021 00000210 00000070 12000004  ...!.......p....
 0134 00000029 00001040 00000000 10000006  ...)...@........
 0144 0000003f 00001040 00000000 11000005  ...?...@........
Contents of section .dynstr:
 0154 005f5f74 6c735f67 65745f61 64647200  .__tls_get_addr.
 0164 5f5a326c 61696900 5f5a3366 6f6f6969  _Z2laii._Z3fooii
 0174 005f5a33 62617276 005f474c 4f42414c  ._Z3barv._GLOBAL
 0184 5f4f4646 5345545f 5441424c 455f005f  _OFFSET_TABLE_._
 0194 44594e41 4d494300                    DYNAMIC.
```

exlbt/input/a.out

```
1-160-136-173:input Jonathan$ ~/llvm/test/cmake_debug_build/Debug/bin/
llvm-objdump -s a.out

a.out:        file format ELF32-CPU0

Contents of section :
...
Contents of section .dynsym:
 013c 00000000 00000000 00000000 00000000  ................
 014c 00000001 00000000 00000000 12000000  ................
 015c 0000000a 00000000 00000000 12000000  ................
Contents of section .dynstr:
 016c 005f5a33 666f6f69 69005f5a 33626172  ._Z3fooii._Z3bar
 017c 76006c69 62666f6f 6261722e 63707530  v.libfoobar.cpu0
 018c 2e736f00                             .so.
...
Contents of section .got.plt:
 2068 00000000 00000000 00000000 00000000  ................
 2078 00000000 00000000 00000000 00000000  ................
 2088 000001d0 00000000 00000000 00000000  ................
 2098 000001e0 00000000 00000000 00000000  ................
Contents of section .data:
 20a8 00000001 00000001 00000001 00000001  ................
```

File dynstr is section .dynstr of libfoobar.cpu0.so. File dynsym is the first 4 bytes of every entry of .dynsym. File global_offset contains the start address of section .got.plt.

The code of dynlinker.v will set the memory as follows after program is loaded. (gp value below is 2068 came from file global_offset).

memory contents

```
//                                    ------------------------------------
// gp ------------------------------> | all 0                              | (16 bytes)
// gp+16 ---------------------------> | 0                          |
// gp+16+1*4 -----------------------> | 1st plt entry address      | (4 bytes)
//                                    | ...                        |
// gp+16+(numDynEntry-1)*4 ---------> | the last plt entry address |
//                                    ------------------------------------
// gpPlt ---------------------------> | all 0                              | (16 bytes)
// gpPlt+16+0*8'h10 ----------------> | 32'h10: pointer to plt0            |
// gpPlt+16+1*8'h10 ----------------> | 1st plt entry                      |
// gpPlt+16+2*8'h10 ----------------> | 2nd plt entry                      |
//                                    | ...                                |
// gpPlt+16+(numDynEntry-1)*8'h10 --> | the last plt entry                 |
//                                    ------------------------------------
```

For example code of ch_dynamiclinker.cpp and foobar.cpp, gp is 2068, numDynEntry is the contents of file num_dyn_entry which is 6. Every plt entry above (memory address gp+16+1*8'h10..gp+16+(numDynEntry-1)*8'h10) is initialized to "addiu $t9, $zero, 4($gp); st $t9, 0($gp); ld $t9, 16($gp); ret $t9" as follows,

memory contents

```
//                                    ------------------------------------
// gp ------------------------------> | all 0                              | (16 bytes)
// gp+16 ---------------------------> | 0                                  |
// gp+16+1*4 -----------------------> | 1st plt entry address              | (4 bytes)
//                                    | ...                                |
// gp+16+(numDynEntry-1)*4 ---------> | the last plt entry address         |
//                                    ------------------------------------
// gpPlt --------------------------> | all 0                                | (16 bytes)
// gpPlt+16+0*8'h10 ----------------> | 32'h10: pointer to plt0              |
// gpPlt+16+1*8'h10 ----------------> | addiu $t9, $zero, 4                  |
//                                    | st  $t9, 0($gp)                      |
//                                    | ld  $t9, 16($gp)                     |
//                                    | ret $t9                              |
// gpPlt+16+2*8'h10 ----------------> | addiu $t9, $zero, 4                  |
//                                    | st  $t9, 0($gp)                      |
//                                    | ld  $t9, 16($gp)                     |
//                                    | ret $t9                              |
// ...                                | ...                                  |
// gpPlt+16+(6-1)*8'h10 ------------> | addiu $t9, $zero, 4                  |
//                                    | st  $t9, 0($gp)                      |
//                                    | ld  $t9, 16($gp)                     |
//                                    | ret $t9                              |
//                                    ------------------------------------
```

Figure 2.9 is the memory contents after the example program is loaded.

Figure 2.10 is the Control flow transfer from call foo() of main() to dynamic linker. After the first time of ch_dynamiclinker.cpp call foo(), it jump to __plt_Z3fooii plt entry. In __plt_Z3fooii, "ld $t9, 1c($gp)" and "ret $t9" will jump to "Plt foo:". Since foo is the 3rd plt entry in "Plt foo:", it save 3 to 0($gp) memory address then jump to PLT0. The purpose of PLT0 is to save $lr, $fp, $sp and jump to dynamic linker. Now, the control flow transfers to dynamic linker. Dynamic linker will get the loaded function name and function offset of shared library by the value of 0($gp) which is 3 now (set in "Plt foo:"). The value 3 tells dynamic linker loading foo() (3rd string in .dynstr) from offset of shared library, 0x3c (3rd value of Function offset area in Figure). Now, dynamic linker can load foo() function from flash to memory, set the address gp+3*4 to 0x40000 where the address 0x40000 is the memory address of foo() function loaded to, and then prepare jump to the foo() memory address. Remind we say the prepare jump to foo(). Because before jump to foo(), dynamic linker needs to restore the $lr, $fp, $sp to the value of just before caller calling foo() (they are saved in 4, 8, 12 of $gp offset in PLT0, so them can be restored from that address).

As Figure 2.11 depicted, control flow from dynamic linker to foo() and back to caller main() when it meets the instruction "ret $lr" in foo().

Now the program run at the next instruction of call foo() in main() as Figure 2.12 depicted. When it runs to address 0xd8 "jsub __plt__Z3barv", the control flow will transfer from main through __plt_Z3barv, "Plt bar:" and PLT0 to dynamic linker as Figure 2.12 depicted. Then load and run bar() from flash to memory just like the calling __plt__Z3fooii as Figure 2.13 depicted. The difference is bar() will call foo() first and call la() next. The call foo() in bar() will jump to foo() directly as Figure 2.12 because the content of gp+28 is the address of 0x40000 which set in dynamic linker when the first time of foo() function is called.

Finally when bar() call la() function it will jump to "Plt la:" since the content of $gp+24 point to "Plt la:". The "Plt la:" code will call dynamic linker to load la() function, run la() and back to bar() as Figure 2.14.

The dynamic linker implementation usually is not specified in ABI. It needs the co-work between linker and dynamic linker/loader. It uses the pointers (the area from gp+16+1*4 to gp+16+(numDynEntry-1)*4). When the code is loaded, this corresponding pointer in this area points to the loaded memory. Otherwise, it points to dynamic linker. The Plt or __plt_Z3fooii, __pltZ3barv are coding in our cpu0PltAtomContent[] of Cpu0RelocationPass.cpp. It is called linkage editor implementation.

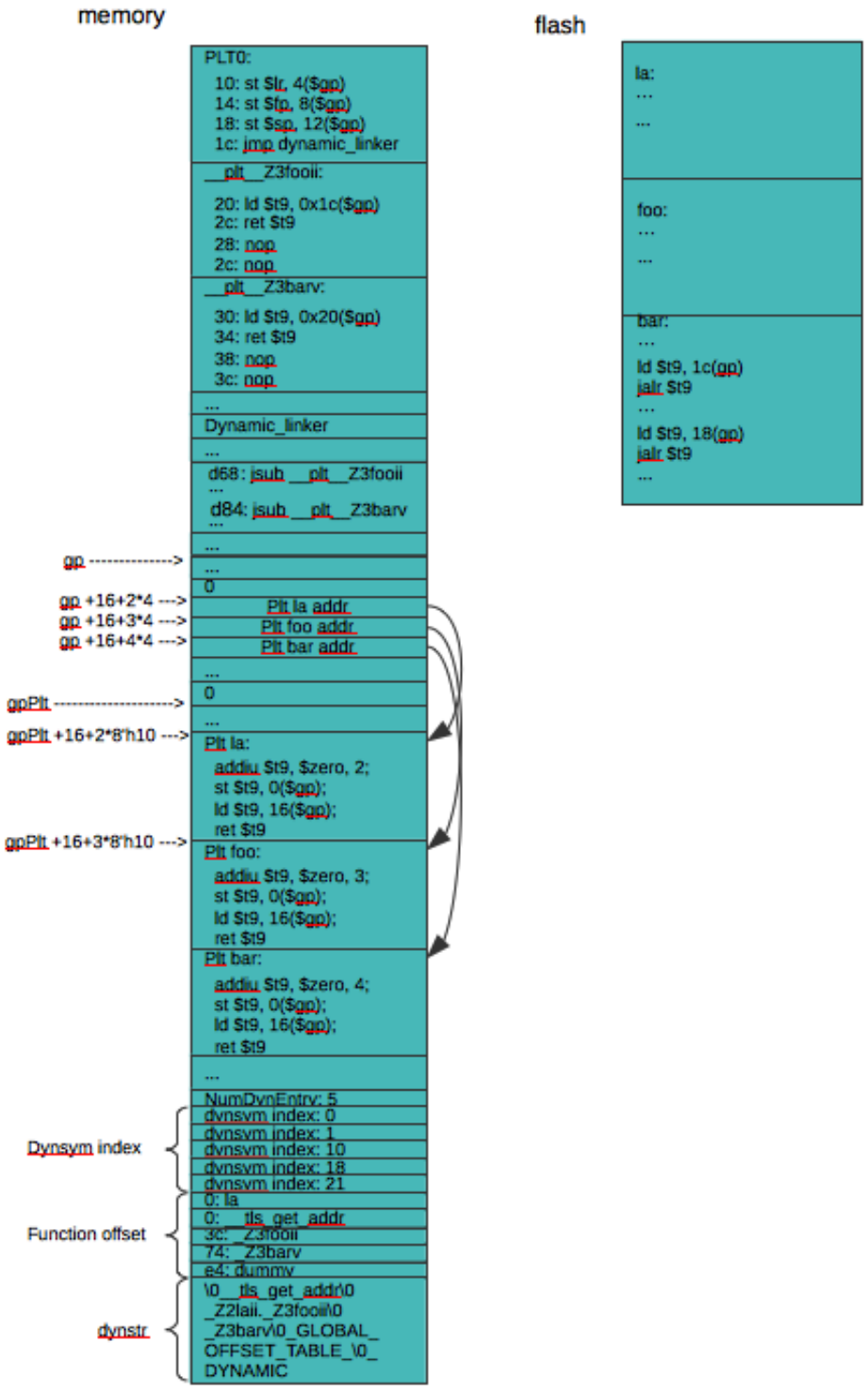

Figure 2.9: Memory contents after the program is loaded

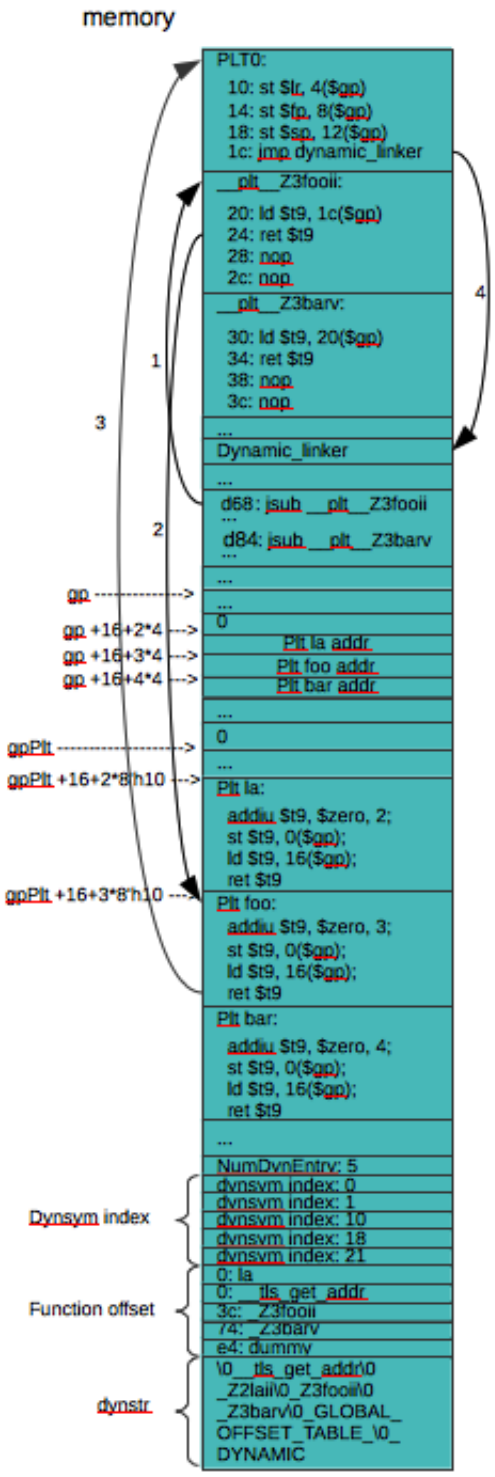

Figure 2.10: Control flow transfer from calling foo() instruction of main() to dynamic linker

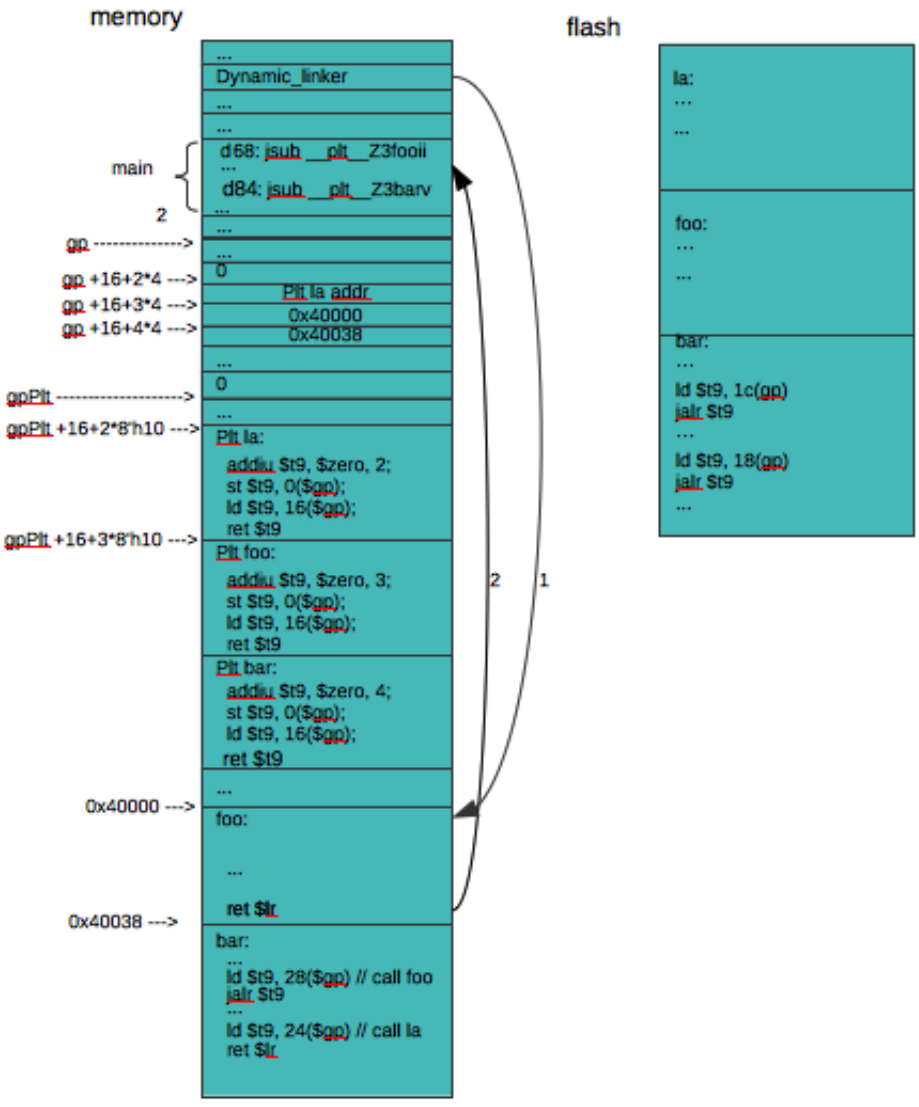

Figure 2.11: Transfer from dynamic linker to foo() and back to main()

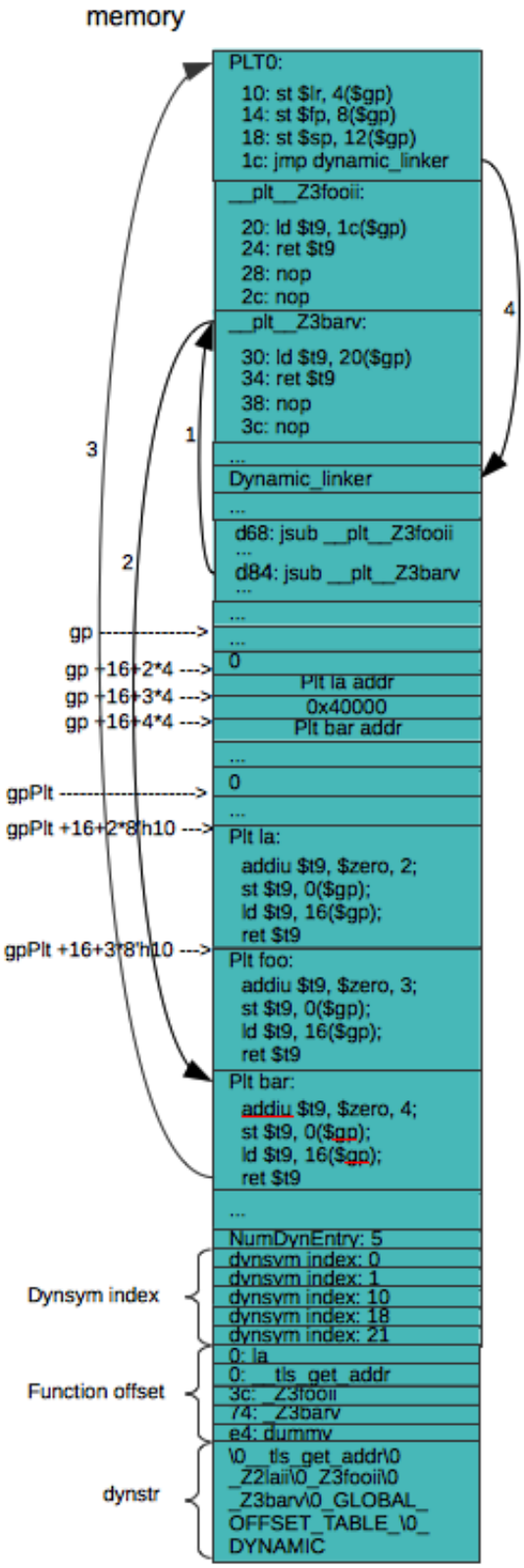

Figure 2.12: Control flow transfer from calling bar() instruction of main() to dynamic linker

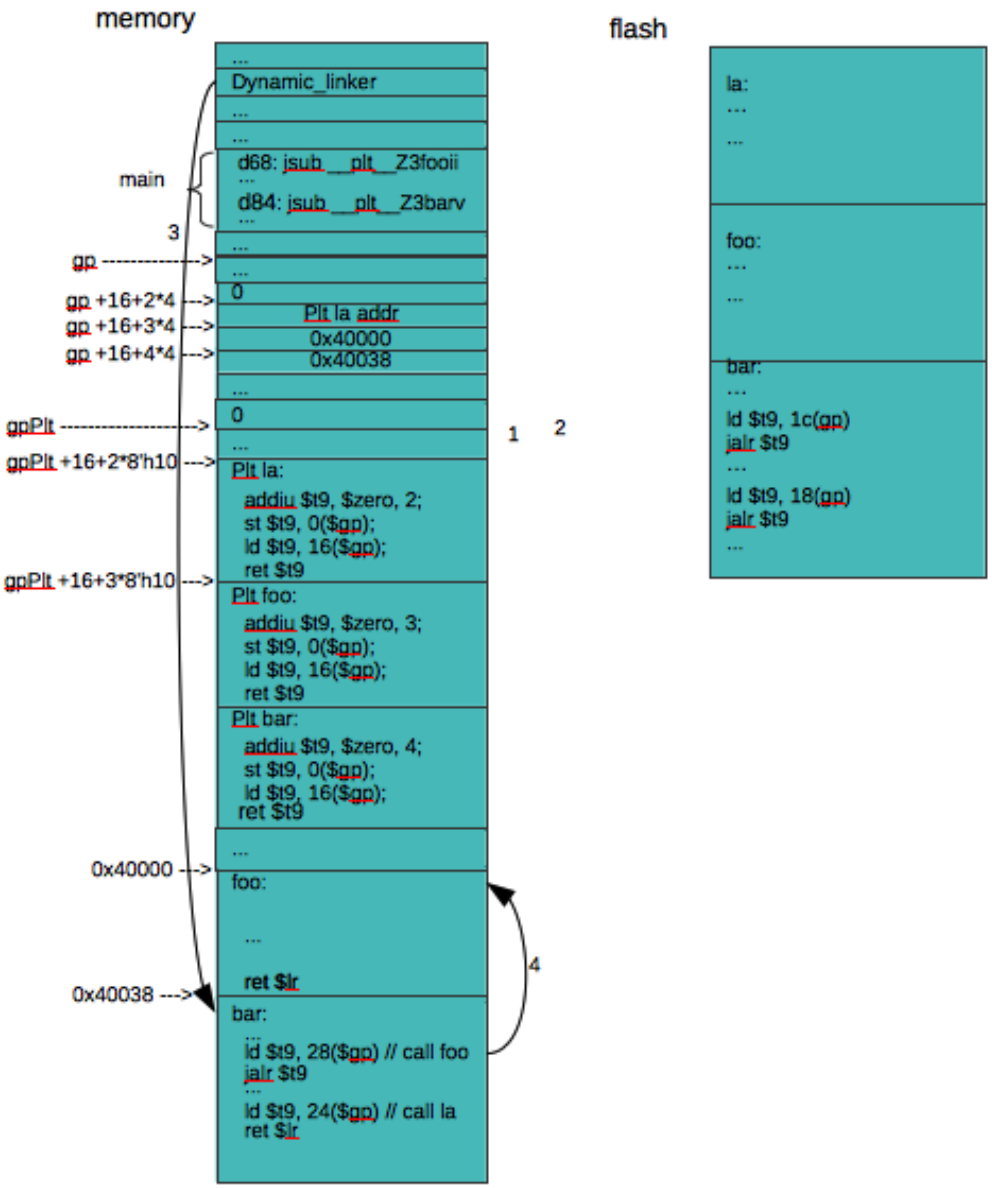

Figure 2.13: Dynamic linker load bar() from flash to memory

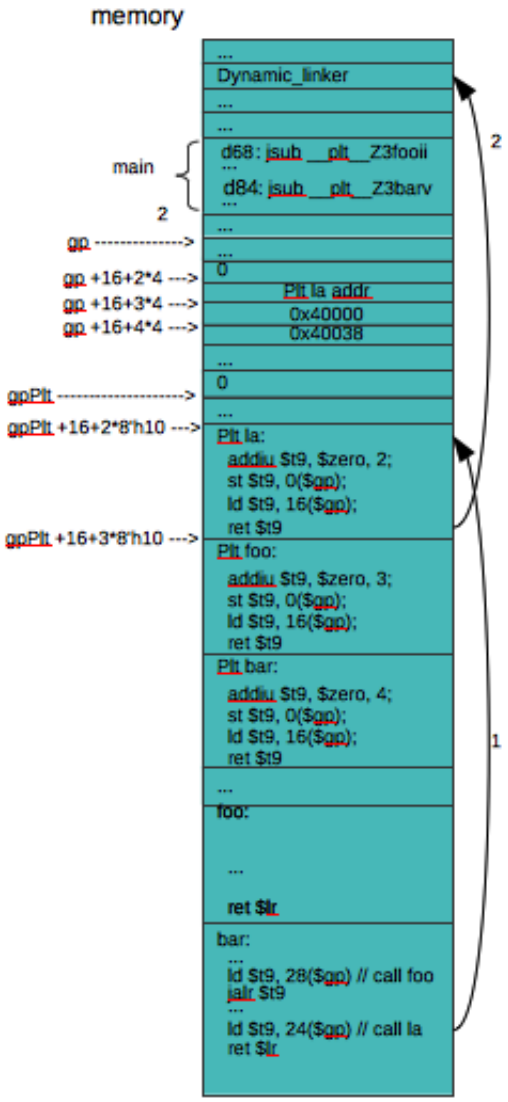

Figure 2.14: Call la through "Plt la:" in bar()

2.3 Summary

2.3.1 Create a new backend base on LLVM

Thanks the llvm open source project. To write a linker and ELF to Hex tools for a new CPU architecture is easy and reliable. Combined with the llvm Cpu0 backend code and Verilog language code programmed in previouse chapters, we design a software toolchain to compile C/C++ code, link and run it on Verilog Cpu0 simulator without any real hardware investment. If you buy the FPGA development hardware, we believe these code can run on FPGA CPU even though we didn't do it. Extend system program toolchain to support a new CPU instruction set can be finished just like we have shown you at this point. School knowledges of system program, compiler, linker, loader, computer architecture and CPU design has been translated into a real work and see how it is running. Now, these school books knowledge is not limited on paper. We design it, program it, and run it on real world.

The total code size of llvm Cpu0 backend compiler, Cpu0 lld linker, llvm-objdump with elf2hex Cpu0 support and Cpu0 Verilog Language is around 10 thousands lines of source code include comments. The total code size of clang, llvm and lld has 1000 thousands lines exclude the test and documents parts. It is only 1 % of the llvm size. More over, the llvm Cpu0 backend and lld Cpu0 backend are 70% of same with llvm Mips and lld X86_64. Based on this truth, we believe llvm is a well defined structure in compiler architecture.

2.3.2 Contribute back to Open Source through working and learning

Finally, 10 thousands lines of source code in Cpu0 backend is very small in UI program. But it's quite complex in system program which based on llvm. We spent 600 pages of pdf to explain these code. Open source code give programmers best opportunity to understand the code and enhance/extend the code function. But it can be better, we believe the documentation is the next most important thing to improve the open source code development. The Open Source Organization recognized this point and set Open Source Document Project years ago [7] [8] [9] [10] [11]. Open Source grows up and becomes a giant software infrastructure with the forces of company [12] [13], school research team and countless talent engineers passion. It terminated the situation of everyone trying to re-invent wheels during 10 years ago. Extend your software from the re-usable source code is the right way. Of course you should consider an open source license if you are working with business. Actually anyone can contribute back to open source through the learning process. This book is written through the process of learning llvm backend and contribute back to llvm open source project. We think this book cannot exists in traditional paper book form since only few number of readers interested in study llvm backend even though there are many paper published books in concept of compiler. So, this book is published via electric media form and try to match the Open Document License Expection [14]. There are distance between the concept and the realistic program implemenation. Keep note through learning a large complicate software such as this llvm backend is not enough. We all learned the knowledge through books during school and after school. So, if you cannot find a good way to produce documents, you can consider to write documents like this book. This book document uses sphinx tool just like the llvm development team. Sphinx uses restructured text format here [15] [16] [17]. Appendix A of lbd book tell you how to install sphinx tool. Documentation work will help yourself to re-examine your software and make your program better in structure, reliability and more important "Extend your code to somewhere you didn't expect".

[7] http://en.wikipedia.org/wiki/BSD_Documentation_License
[8] http://www.freebsd.org/docproj/
[9] http://www.freebsd.org/copyright/freebsd-doc-license.html
[10] http://en.wikipedia.org/wiki/GNU_Free_Documentation_License
[11] http://www.gnu.org/copyleft/fdl.html
[12] http://www.apple.com/opensource/
[13] https://www.ibm.com/developerworks/opensource/
[14] http://www.gnu.org/philosophy/free-doc.en.html
[15] http://docutils.sourceforge.net/docs/ref/rst/restructuredtext.html
[16] http://docutils.sourceforge.net/docs/ref/rst/directives.html
[17] http://docutils.sourceforge.net/rst.html

CHAPTER

THREE

OPTIMIZATION

- LLVM IR optimization
- Project
  - LLVM-VPO

This chapter introduce llvm optimization.

3.1 LLVM IR optimization

The llvm-link provide optimizaton in IR level which can apply in different programs developed by more than one language. Of course, it can apply in the same language which support seperate compile.

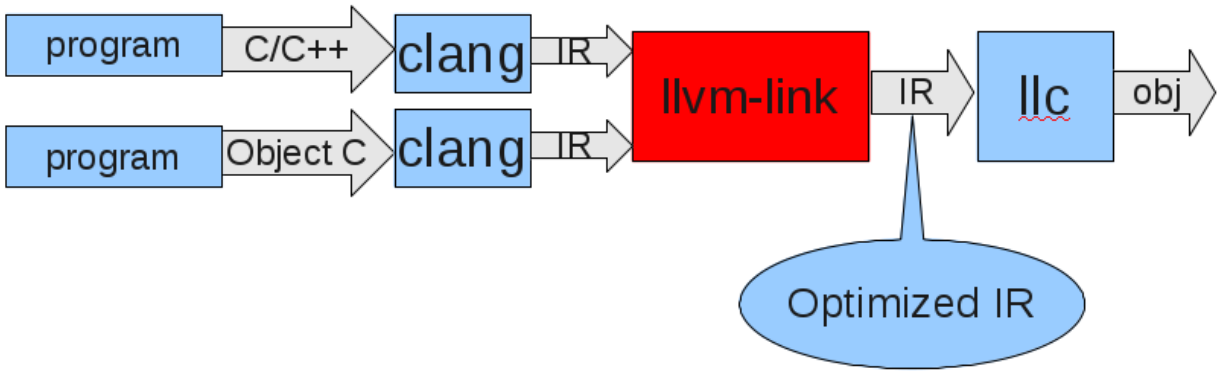

Figure 3.1: llvm-link flow

Clang provide optimization options to do optimation from high level language to IR. But since many languages like C/C++ support separate compilation, it meaning there is no chance to do inter-procedure optimization if the functions come from different source files. To solve this problem, llvm provide **llvm-link** to link all *.bc into a single IR file, and through **opt** to finish the inter-procedure optimation [1]. Beyond the DAG local optimization mentioned in Chapter 2, there are global optimization based on inter-procedure analysis [2]. The following steps and examples show this optimization solution in llvm.

[1] http://www.cs.cmu.edu/afs/cs/academic/class/15745-s12/public/lectures/L3-LLVM-Part1.pdf
[2] Refer chapter 9 of book Compilers: Principles, Techniques, and Tools (2nd Edition)

exlbt/input/optimizen/1.cpp

```
int callee(const int *a) {
  return *a+1;
}
```

exlbt/input/optimize/2.cpp

```
extern int callee(const int *X);

int caller() {
  int T;

  T = 4;

  return callee(&T);
}
```

```
JonathantekiiMac:input Jonathan$ clang -O3 -target mips-unknown-linux-gnu
-c 1.cpp -emit-llvm -o 1.bc
JonathantekiiMac:input Jonathan$ clang -O3 -target mips-unknown-linux-gnu
-c 2.cpp -emit-llvm -o 2.bc
JonathantekiiMac:input Jonathan$ llvm-link -o=a.bc 1.bc 2.bc
JonathantekiiMac:input Jonathan$ opt -O3 -o=a1.bc a.bc
JonathantekiiMac:input Jonathan$ llvm-dis a.bc -o -
...
; Function Attrs: nounwind readonly
define i32 @_Z6calleePKi(i32* nocapture readonly %a) #0 {
  %1 = load i32* %a, align 4, !tbaa !1
  %2 = add nsw i32 %1, 1
  ret i32 %2
}

define i32 @_Z6callerv() #1 {
  %T = alloca i32, align 4
  store i32 4, i32* %T, align 4, !tbaa !1
  %1 = call i32 @_Z6calleePKi(i32* %T)
  ret i32 %1
}
...

JonathantekiiMac:input Jonathan$ llvm-dis a1.bc -o -
...
; Function Attrs: nounwind readonly
define i32 @_Z6calleePKi(i32* nocapture readonly %a) #0 {
  %1 = load i32* %a, align 4, !tbaa !1
  %2 = add nsw i32 %1, 1
  ret i32 %2
}

; Function Attrs: nounwind readnone
define i32 @_Z6callerv() #1 {
  ret i32 5
}
...
```

From the result as above, the **opt** output has lesser number of IR instructions. Of course, the backend code will be

more effective as follows,

```
JonathantekiiMac:input Jonathan$ /Users/Jonathan/llvm/test/cmake_debug_build/
bin/Debug/llc -march=cpu0 -relocation-model=pic -filetype=asm a.bc -o -
        .section .mdebug.abi32
        .previous
        .file "a.bc"
        .text
        .globl        _Z6calleePKi
        .align        2
        .type _Z6calleePKi,@function
        .ent  _Z6calleePKi            # @_Z6calleePKi
_Z6calleePKi:
        .frame        $sp,0,$lr
        .mask         0x00000000,0
        .set  noreorder
        .set  nomacro
# BB#0:
        ld    $2, 0($sp)
        ld    $2, 0($2)
        addiu $2, $2, 1
        ret   $lr
        .set  macro
        .set  reorder
        .end  _Z6calleePKi
$tmp0:
        .size _Z6calleePKi, ($tmp0)-_Z6calleePKi

        .globl        _Z6callerv
        .align        2
        .type _Z6callerv,@function
        .ent  _Z6callerv              # @_Z6callerv
_Z6callerv:
        .cfi_startproc
        .frame        $sp,32,$lr
        .mask         0x00004000,-4
        .set  noreorder
        .cpload       $t9
        .set  nomacro
# BB#0:
        addiu $sp, $sp, -32
$tmp3:
        .cfi_def_cfa_offset 32
        st    $lr, 28($sp)            # 4-byte Folded Spill
$tmp4:
        .cfi_offset 14, -4
        .cprestore    8
        addiu $2, $zero, 4
        st    $2, 24($sp)
        addiu $2, $sp, 24
        st    $2, 0($sp)
        ld    $t9, %call16(_Z6calleePKi)($gp)
        jalr  $t9
        ld    $gp, 8($sp)
        ld    $lr, 28($sp)            # 4-byte Folded Reload
        addiu $sp, $sp, 32
        ret   $lr
        .set  macro
        .set  reorder
```

```
        .end  _Z6callerv
$tmp5:
        .size _Z6callerv, ($tmp5)-_Z6callerv
        .cfi_endproc

JonathantekiiMac:input Jonathan$ /Users/Jonathan/llvm/test/cmake_debug_build/
bin/Debug/llc -march=cpu0 -relocation-model=pic -filetype=asm a1.bc -o -
        .section .mdebug.abi32
        .previous
        .file "a1.bc"
        .text
        .globl        _Z6calleePKi
        .align        2
        .type _Z6calleePKi,@function
        .ent  _Z6calleePKi            # @_Z6calleePKi
_Z6calleePKi:
        .frame        $sp,0,$lr
        .mask         0x00000000,0
        .set  noreorder
        .set  nomacro
# BB#0:
        ld    $2, 0($sp)
        ld    $2, 0($2)
        addiu $2, $2, 1
        ret   $lr
        .set  macro
        .set  reorder
        .end  _Z6calleePKi
$tmp0:
        .size _Z6calleePKi, ($tmp0)-_Z6calleePKi

        .globl        _Z6callerv
        .align        2
        .type _Z6callerv,@function
        .ent  _Z6callerv              # @_Z6callerv
_Z6callerv:
        .frame        $sp,0,$lr
        .mask         0x00000000,0
        .set  noreorder
        .set  nomacro
# BB#0:
        addiu $2, $zero, 5
        ret   $lr
        .set  macro
        .set  reorder
        .end  _Z6callerv
$tmp1:
        .size _Z6callerv, ($tmp1)-_Z6callerv
```

Though llvm-link provide optimization in IR level to support seperate compile, it come with the cost in compile time. As you can imagine, any one statement change will change the output IR of llvm-link. And the obj binary code have to re-compile. Compare to the seperate compile for each *.c file, it only need to re-compile the corresponding *.o file only.

3.2 Project

3.2.1 LLVM-VPO

Friend Gang-Ryung Uh replace LLC compiler by llvm on Very Portable Optimizer (VPO) compiler toolchain. VPO performs optimizations on a single intermediate representation called Register Transfer Lists (RTLs). In other word, the system generate RTLs from llvm IR and it do further optimization on RTLs.

The LLVM-VPO is illustrated at his home page. Click **"6. LLVM-VPO Compiler Development - 2012 Google Faculty Research Award"** at this home page [3] will get the information.

[3] http://cs.boisestate.edu/~uh/

CHAPTER

FOUR

LIBRARY

- Compiler-rt
- Avr libc
- Software Float Point Support

Since Cpu0 has not hardware float point instructions, it needs soft float point library to finish the floating point operation. LLVM compiler-rt project include the software floating point library implementation, so we choose it as the implementation.

Since compiler-rt uses unix/linux rootfs structure, we fill the gap by porting avr libc.

Both the compiler-rt and avr libc porting is under going, it's not finished. The flow as follows,

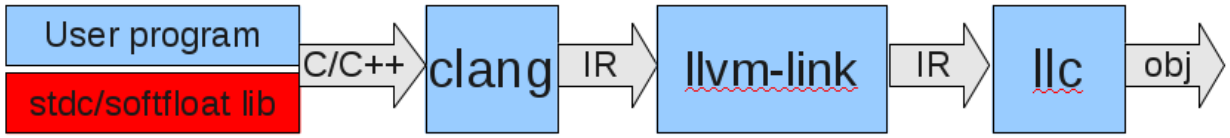

Figure 4.1: libc/softfloat library flow

The llvm-link which introduced at last chapter can be hired for optimization.

4.1 Compiler-rt

Directory libex/libsoftfloat/compiler-rt include the floating point library support for Cpu0 backend. The compiler-rt [1] version we use is llvm 3.5 release.

4.2 Avr libc

Directory libex/libc/avr-libc-1.8.1 include the libc porting.

AVR Libc is a Free Software project whose goal is to provide a high quality C library for use with GCC on Atmel AVR microcontrollers. AVR Libc is licensed under a single unified license. This so-called modified Berkeley license is intented to be compatible with most Free Software licenses like the GPL, yet impose as little restrictions for the use of the library in closed-source commercial applications as possible [2].

[1] http://compiler-rt.llvm.org/
[2] http://www.nongnu.org/avr-libc/

The source code can be download from here [3]. Document are here [4] [5].

4.3 Software Float Point Support

exlbt/input/ch_float.cpp

```
#include "debug.h"

#define SINGLE_PRECISION
#include "fp_lib.h"

extern "C" int __fixsfsi(fp_t a);
extern "C" int __fixdfsi(double a);

extern long long test_longlong_shift1();
extern long long test_longlong_shift2();

#include "print.cpp"

int test_float_to_int()
{
  float a = -2.2;
  si_int c = __fixsfsi(a);

  return c;
}

// work
int test_double_to_int()
{
  double a = -4.2;
  si_int c = __fixdfsi(a);

  return c;
}

#include "int_lib.h"

extern "C" int printf(const char *format, ...);
extern "C" int sprintf(char *out, const char *format, ...);

int test_float_add()
{
  float a = -2.2;
  float b = 3.3;

  int c = (int)(a + b); // 1

  return c;
}

int test_float_mul()
```

[3] http://download.savannah.gnu.org/releases/avr-libc/
[4] http://www.atmel.com/webdoc/AVRLibcReferenceManual/index.html
[5] http://courses.cs.washington.edu/courses/csep567/04sp/pdfs/avr-libc-user-manual.pdf

```
{
  float a = -2.2;
  float b = 3.3;
  float c = -4.3;

  int d = (int)(a * b * c); // 31.218=31

  return d;
}

int test_float_div()
{
  float a = -2.2;
  float b = 3.3;
  float c = 1.2;

  int d = (int)((a * b) / c); // -6

  return d;
}

int test_double_to_int_2()
{
  double b = 3.3;

  int c = (int)(b);

  return c;
}

int test_double_add()
{
  double a = 2.2;
  double b = 3.3;

  int c = (int)(a + b);

  return c;
}

int test_double_mul()
{
  double a = -2.2;
  double b = 3.3;
  double c = 4.3;

  int d = (int)(a * b * c); // -31.218=-31

  return d;
}

int test_double_div()
{
  double a = -2.2;
  double b = 3.3;
  double c = 1.2;

  int d = (int)((a * b) / c); // -6
```

```
  return d;
}

#if 0
//extern "C" di_int __addvdi3(di_int a, di_int b);
extern "C" di_int __addvdi3(long long a, long long b);

//int test__addvdi3(di_int a, di_int b)
int test__addvdi3(long long a, long long b)
{
    di_int x = __addvdi3(a, b);
    di_int expected = a + b;
    if (x != expected)
        printf("error in test__addvdi3(0x%llX, 0x%llX) = %lld, expected %lld\n",
               a, b, x, expected);
    return x != expected;
}

int test_addvdi3()
{
//     test__addvdi3(0x8000000000000000LL, -1);  // should abort
//     test__addvdi3(-1, 0x8000000000000000LL);  // should abort
//     test__addvdi3(1, 0x7FFFFFFFFFFFFFFFLL);  // should abort
//     test__addvdi3(0x7FFFFFFFFFFFFFFFLL, 1);  // should abort

    if (test__addvdi3(0x8000000000000000LL, 1))
        return 1;
    if (test__addvdi3(1, 0x8000000000000000LL))
        return 1;
    if (test__addvdi3(0x8000000000000000LL, 0))
        return 1;
    if (test__addvdi3(0, 0x8000000000000000LL))
        return 1;
    if (test__addvdi3(0x7FFFFFFFFFFFFFFFLL, -1))
        return 1;
    if (test__addvdi3(-1, 0x7FFFFFFFFFFFFFFFLL))
        return 1;
    if (test__addvdi3(0x7FFFFFFFFFFFFFFFLL, 0))
        return 1;
    if (test__addvdi3(0, 0x7FFFFFFFFFFFFFFFLL))
        return 1;

    return 0;
}
#endif


extern "C" di_int __absvdi2(di_int a);

int test__absvdi2(di_int a)
{
    di_int x = __absvdi2(a);
    di_int expected = a;
    if (expected < 0)
        expected = -expected;
    if (x != expected || expected < 0)
        printf("error in __absvdi2(0x%08X%08X) = %08d%08d, expected positive %08d%08d\n",
               (int)(a>>32), (int)a, (int)(x>>32), (int)x, int(expected>>32), (int)expected);
```

```
    return x != expected;
}

int test_absvdi2()
{
//     if (test__absvdi2(0x8000000000000000LL))  // should abort
//         return 1;
    test__absvdi2(0x0000000000000000LL);
    test__absvdi2(0x0000000000000001LL);
    test__absvdi2(0x0000000000000002LL);
    test__absvdi2(0x7FFFFFFFFFFFFFFELL);
    test__absvdi2(0x7FFFFFFFFFFFFFFFLL);
    test__absvdi2(0x8000000000000001LL);
    test__absvdi2(0x8000000000000002LL);
    test__absvdi2(0xFFFFFFFFFFFFFFFELL);
    test__absvdi2(0xFFFFFFFFFFFFFFFFLL);

    int i;
    for (i = 0; i < 100; ++i)
        if (test__absvdi2(((di_int)i << 32) | 1))
            return 1;

    return 0;
}

extern "C" si_int __absvsi2(si_int a);

int test__absvsi2(si_int a)
{
    si_int x = __absvsi2(a);
    si_int expected = a;
    if (expected < 0)
        expected = -expected;
    if (x != expected || expected < 0)
        printf("error in __absvsi2(0x%X) = %d, expected positive %d\n",
               a, x, expected);
    return x != expected;
}

int test_absvsi2()
{
//     if (test__absvsi2(0x80000000))  // should abort
//         return 1;
    test__absvsi2(0x00000000);
    test__absvsi2(0x00000001);
    test__absvsi2(0x00000002);
    test__absvsi2(0x7FFFFFFE);
    test__absvsi2(0x7FFFFFFF);
    test__absvsi2(0x80000001);
    test__absvsi2(0x80000002);
    test__absvsi2(0xFFFFFFFE);
    test__absvsi2(0xFFFFFFFF);

    int i;
    for (i = 0; i < 100; ++i)
        if (test__absvsi2(i))
            return 1;
```

```
    return 0;
}

#if 0
#define CRT_HAS_128BIT

#ifdef CRT_HAS_128BIT

// Returns: absolute value

// Effects: aborts if abs(x) < 0

extern "C" ti_int __absvti2(ti_int a);

int test__absvti2(ti_int a)
{
    ti_int x = __absvti2(a);
    ti_int expected = a;
    if (expected < 0)
        expected = -expected;
    if (x != expected || expected < 0)
    {
        twords at;
        at.all = a;
        twords xt;
        xt.all = x;
        twords expectedt;
        expectedt.all = expected;
        printf("error in __absvti2(0x%8X%8X.%8X%8X) = "
               "0x%8X%8X%.8X%.8X, expected positive 0x%8X%8X%.8X%.8X\n",
               (int)(at.s.high>>32), (int)(at.s.high), (int)(at.s.low>>32),
               (int)(at.s.low), (int)(xt.s.high>>32), (int)(xt.s.high),
               (int)(xt.s.low>>32), (int)(xt.s.low),
               (int)(expectedt.s.high>>32), (int)(expectedt.s.high),
               (int)(expectedt.s.low>>32), (int)(expectedt.s.low));
    }
    return x != expected;
}

#endif

int test_absvti2()
{
#ifdef CRT_HAS_128BIT

//     if (test__absvti2(make_ti(0x8000000000000000LL, 0)))  // should abort
//         return 1;
    if (test__absvti2(0x0000000000000000LL))
        return 1;
    if (test__absvti2(0x0000000000000001LL))
        return 1;
    if (test__absvti2(0x0000000000000002LL))
        return 1;
    if (test__absvti2(make_ti(0x7FFFFFFFFFFFFFFFLL, 0xFFFFFFFFFFFFFFFELL)))
        return 1;
    if (test__absvti2(make_ti(0x7FFFFFFFFFFFFFFFLL, 0xFFFFFFFFFFFFFFFFLL)))
        return 1;
    if (test__absvti2(make_ti(0x8000000000000000LL, 0x0000000000000001LL)))
```

```
        return 1;
    if (test__absvti2(make_ti(0x8000000000000000LL, 0x0000000000000002LL)))
        return 1;
    if (test__absvti2(make_ti(0xFFFFFFFFFFFFFFFFLL, 0xFFFFFFFFFFFFFFFELL)))
        return 1;
    if (test__absvti2(make_ti(0xFFFFFFFFFFFFFFFFLL, 0xFFFFFFFFFFFFFFFFLL)))
        return 1;

    int i;
    for (i = 0; i < 10000; ++i)
        if (test__absvti2(make_ti(((ti_int)i << 32) | i,
                                  ((ti_int)i << 32) | i)))
            return 1;
#else
    printf("skipped\n");
#endif
    return 0;
}
#endif

int main() {
  int a;

  a = test_longlong_shift1(); // 0x121 = 289
  printf("test_longlong_shift1() = %d\n", a);
  a = test_longlong_shift2(); // 0x16 = 22
  printf("test_longlong_shift2() = %d\n", a);
  a = test_float_to_int(); // -2
  printf("test_float_to_int() = %d\n", a);
  a = test_double_to_int(); // -4
  printf("test_double_to_int() = %d\n", a);
  a = test_double_to_int_2(); // 3
  printf("test_double_to_int_2() = %d\n", a);
  a = test_float_add(); // 1
  printf("test_float_add() = %d\n", a);
  a = test_float_mul(); // 31
  printf("test_float_mul() = %d\n", a);
  a = test_float_div(); // -6
  printf("test_float_div() = %d\n", a);
  a = test_double_add(); // 5
  printf("test_double_add() = %d\n", a);
  a = test_double_mul(); // -31
  printf("test_double_mul() = %d\n", a);
  a = test_double_div(); // -6
  printf("test_double_div() = %d\n", a);

#if 0
  test_addvdi3();
#endif
  test_absvdi2();
  test_absvsi2();

  return 0;
}
```

exlbt/input/build-float.sh

```
#!/usr/bin/env bash

INCFLAG="-I../libsoftfloat/compiler-rt/builtins"

source functions.sh

sh_name=build-float.sh
argNum=$#
arg1=$1
arg2=$2

prologue;

libsf=../libsoftfloat/compiler-rt
pushd ${libsf}
bash build.sh
popd
olibsf=${libsf}/obj

clang -target mips-unknown-linux-gnu -c start.cpp -emit-llvm -o start.bc
clang -target mips-unknown-linux-gnu -c debug.cpp -emit-llvm -o debug.bc
clang -target mips-unknown-linux-gnu -c printf-stdarg-def.c -emit-llvm \
-o printf-stdarg-def.bc
clang -target mips-unknown-linux-gnu -c printf-stdarg.c -emit-llvm \
-o printf-stdarg.bc
clang $INCFLAG -c ch_float.cpp -emit-llvm -o ch_float.bc
clang $INCFLAG -c ${LBDEXDIR}/input/ch9_7.cpp -emit-llvm -o ch9_7.bc
${TOOLDIR}/llc -march=cpu0${endian} -mcpu=${CPU} -relocation-model=static \
-filetype=obj start.bc -o start.cpu0.o
${TOOLDIR}/llc -march=cpu0${endian} -mcpu=${CPU} -relocation-model=static \
-filetype=obj debug.bc -o debug.cpu0.o
${TOOLDIR}/llc -march=cpu0${endian} -mcpu=${CPU} -relocation-model=static \
-filetype=obj printf-stdarg-def.bc -o printf-stdarg-def.cpu0.o
${TOOLDIR}/llc -march=cpu0${endian} -mcpu=${CPU} -relocation-model=static \
-filetype=obj printf-stdarg.bc -o printf-stdarg.cpu0.o
${TOOLDIR}/llc -march=cpu0${endian} -mcpu=${CPU} -relocation-model=static \
-filetype=obj ch9_7.bc -o ch9_7.cpu0.o
${TOOLDIR}/llc -march=cpu0${endian} -mcpu=${CPU} -relocation-model=static \
-filetype=obj ch_float.bc -o ch_float.cpu0.o
${TOOLDIR}/llc -march=cpu0${endian} -mcpu=${CPU} -relocation-model=static \
-filetype=obj lib_cpu0.ll -o lib_cpu0.o
${TOOLDIR}/lld -flavor gnu -target cpu0${endian}-unknown-linux-gnu \
  -o a.out start.cpu0.o debug.cpu0.o printf-stdarg-def.cpu0.o printf-stdarg.cpu0.o \
  ch_float.cpu0.o ch9_7.cpu0.o lib_cpu0.o \
  ${olibsf}/libFloat.o
#  ${olibsf}/fixsfsi.o ${olibsf}/fixsfdi.o ${olibsf}/fixdfsi.o \
#  ${olibsf}/addsf3.o ${olibsf}/mulsf3.o ${olibsf}/divsf3.o \
#  ${olibsf}/adddf3.o ${olibsf}/muldf3.o ${olibsf}/divdf3.o \
#  ${olibsf}/ashrdi3.o ${olibsf}/ashldi3.o ${olibsf}/lshrdi3.o \
#  ${olibsf}/extendsfdf2.o ${olibsf}/truncdfsf2.o


epilogue;
```

Run as follows,

```
JonathantekiiMac:input Jonathan$ bash build-float.sh cpu032II be
...
endian =  BigEndian
0   /* 0: big endian, 1: little endian */

JonathantekiiMac:input Jonathan$ iverilog -o cpu0IIs cpu0IIs.v
JonathantekiiMac:input Jonathan$ ./cpu0IIs
114-43-184-210:verilog Jonathan$ ./cpu0IIs
WARNING: ./cpu0.v:458: $readmemh(cpu0.hex): Not enough words in the file for
the requested range [0:524287].
taskInterrupt(001)
test_longlong_shift1() = 289
test_longlong_shift2() = 22
test_float_to_int() = -2
test_double_to_int() = -4
test_double_to_int_2() = 3
test_float_add() = 1
test_float_mul() = 31
test_float_div() = -6
test_double_add() = 5
test_double_mul() = -31
test_double_div() = -6
total cpu cycles = 104105
RET to PC < 0, finished!
```

CHAPTER

FIVE

BOOK EXAMPLE CODE

The example code exlbt.tar.gz is available in:

http://jonathan2251.github.io/lbt/exlbt.tar.gz

CHAPTER

SIX

ALTERNATE FORMATS

The book is also available in the following formats: