C++ exception handling

MaskRay

https://maskray.me

MaskRay

- LLVM contributor

MaskRay

- LLVM contributor
- https://github.com/MaskRay/ccls (C++ language server)

MaskRay

- LLVM contributor
- `https://github.com/MaskRay/ccls` (C++ language server)
- Retired Algo/HPC/CTF player

Recent work (2020-08-01 to now)

- gcov (code coverage)
- LLD (linker)
- `-gz`, `-cc1as`
- integrated assembler
- debug information
- `llvm-objcopy --only-keep-debug` for Android bionic
- profile-guided optimization
- language-specific data area (LSDA)

gcov

- `-m`: demangled function names
- `--relative`: skip system headers (and other files with absolute paths)
- `--source-only prefix`
- Interaction with `-fsanitize=thread`: gcov is very early in the pipeline, Thread Sanitizer is much late.
- Optimization: Kirchhoff's circuit law
- `https://maskray.me/blog/2020-09-27-gcov-and-llvm`

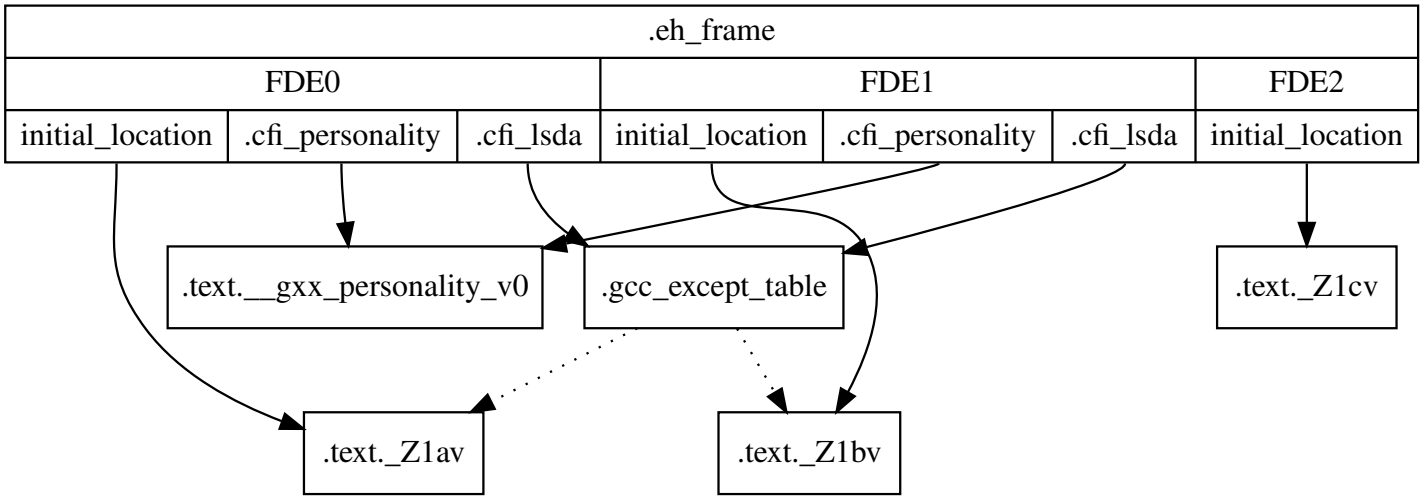
C++ exceptions

- Non-local jump to an exception handler in an ancestor call frame
- The control flow continues to unwind the stack (destructors are called for all fully-constructed non-static members and base classes)
- `std::terminate()` if no handler exists

```
void foo() { throw 0xB612; }
void bar() { B b; foo(); }
void qux() { try { A a; bar(); } catch (int x) {} }
```

Itanium C++ ABI: Exception Handling

- 2 parts: Level 1 Base ABI and Level 2 C++ ABI
- Base ABI: stack unwinding, common to all languages
  - `_Unwind_*` (`_Unwind_RaiseException` (two-phase process), _Unwind_Resume)
  - Impl: `.eh_frame_hdr`, `.eh_frame`, `libgcc_s.so.1`/`libgcc_eh.a`/libunwind (`--unwindlib=libunwind`)
- C++ ABI: interoperability of C++ implementations
  - `__cxa_*` (`__cxa_allocate_exception`, `__cxa_throw`, `__cxa_begin_catch`), personality, language-specific data area
  - Impl: `.gcc_except_table`, `libsupc++`, `libc++abi.(a|so)`



- `.eh_frame` contains CIE (Common Information Entry) and FDE (Frame Description Entry)
- CIE references a personality routine in `.text`
- FDE references language-specific data area in `.gcc_except_table`
- Dotted edges are present only if basic block sections or RISC-V `-mrelax`, i.e. LSDA normally has no relocation

```
static _Unwind_Reason_Code unwind_phase1(unw_context_t *uc, _Unwind_Context *ctx,
                                         _Unwind_Exception *obj) {
  // Search phase: unwind and call personality with _UA_SEARCH_PHASE for each frame
  // until a handler (catch block) is found.
}
static _Unwind_Reason_Code unwind_phase2(unw_context_t *uc, _Unwind_Context *ctx,
                                         _Unwind_Exception *obj) {
  // Cleanup phase: unwind and call personality with _UA_CLEANUP_PHASE for each frame
  // until reaching the handler. Restore the register state and transfer control.
}
_Unwind_Reason_Code _Unwind_RaiseException(_Unwind_Exception *obj) {
  unw_context_t uc; __unw_getcontext(&uc);
  _Unwind_Context ctx;
  _Unwind_Reason_Code phase1 = unwind_phase1(&uc, &ctx, obj);
  if (phase1 != _URC_NO_REASON) return phase1;
  unwind_phase2(&uc, &ctx, obj);
}
void __cxa_throw(void *thrown, std::type_info *tinfo, void (*destructor)(void *)) {
  uncaughtExceptions++;
  __cxa_exception *hdr = (__cxa_exception *)thrown - 1;
  hdr->exceptionType = tinfo; hdr->destructor = destructor;
  _Unwind_RaiseException(&hdr->unwindHeader);
  // Failed to unwind, e.g. the .eh_frame FDE is absent.
  __cxa_begin_catch(&hdr->unwindHeader); std::terminate();
}
void foo() { __cxa_exception *thrown = __cxa_allocate_exception(4); *thrown = 42;
             __cxa_throw(thrown, &typeid(int), /*destructor=*/nullptr); }
void bar() { B b; qux(); return; landing_pad: b.~B(); _Unwind_Resume(); }
// void qux() { try { A a; bar(); } catch (int x) {} }
void qux() { A a; bar(); return; landing_pad: __cxa_begin_catch(obj); __cxa_end_catch(obj); }
```

Life of an exception

- `foo` allocates a `__cxa_exception` object, sets the thrown value, and calls `__cxa_throw`
- `__cxa_throw` sets fields in the header (type info, destructor, etc) and call Base ABI specified `_Unwind_RaiseException` (on error: `std::terminate()`)
- `_Unwind_RaiseException` calls `unw_phase1` and then `unw_phase2`
- `unw_phase1` locates the matching catch block
- `unw_phase2` transfers control to a cleanup handler
- The handler performs cleanup and jumps back via `_Unwind_Resume`
- `unw_phase2` eventually transfers control to the matching catch block
- The final landing pad returns the exception object via `__cxa_begin_catch`

```
// Find .eh_frame CIE/FDE associated with the IP stored in ctx.
// Get personality and LSDA from CIE and FDE.
static void unw_init_local(unw_context_t *uc, _Unwind_Context *ctx) {
  Iterate PT_GNU_EH_FRAME (.eh_frame_hdr) and find the one defining IP.
  Find the .eh_frame FDE referenced by the .eh_frame_hdr entry.
  Find the .eh_frame CIE referenced by the CIE.
  ctx->start_ip = fdeInfo.pcStart; ctx->end_ip = fdeInfo.pcEnd;
  ctx->lsda = fdeInfo.lsda; ctx->personality = cieInfo.personality;
}
// Execute .cfi_* to restore PC, SP, and other callee-saved registers in ctx
static bool step(_Unwind_Context *ctx) { ... }

static _Unwind_Reason_Code unwind_phase1(unw_context_t *uc, _Unwind_Context *ctx,
                                         _Unwind_Exception *obj) {
  unw_init_local(uc, ctx);
  for(;;) {
    if (ctx->fdeMissing) return _URC_END_OF_STACK;
    if (!step(ctx)) return _URC_FATAL_PHASE1_ERROR;
    ctx->getFdeAndCieFromIP();
    if (!ctx->personality) continue;
    switch (ctx->personality(1, _UA_SEARCH_PHASE, obj->exception_class, obj, ctx)) {
    case _URC_CONTINUE_UNWIND: break;
    case _URC_HANDLER_FOUND:
      unw_get_reg(ctx, UNW_REG_SP, &obj->private_2);
      return _URC_NO_REASON;
    default: return _URC_FATAL_PHASE1_ERROR; // e.g. stack corruption
    }
  }
  return _URC_NO_REASON;
}
```

```
static void unw_resume(_Unwind_Exception *ctx) {
  Jump to a landing pad (cleanup or the matching catch block).
  Similar to longjmp: set callee-saved registers, SP and IP.
}

static _Unwind_Reason_Code unwind_phase2(unw_context_t *uc, _Unwind_Context *ctx,
                                         _Unwind_Exception *obj) {
  unw_init_local(uc, ctx);
  for(;;) {
    if (ctx->fdeMissing) return _URC_END_OF_STACK;
    if (!step(ctx)) return _URC_FATAL_PHASE2_ERROR;
    ctx->getFdeAndCieFromIP();
    if (!ctx->personality) continue;
    _Unwind_Action action = _UA_CLEANUP_PHASE;
    size_t sp;
    unw_get_reg(ctx, UNW_REG_SP, &sp);
    if (sp == obj->private_2) action |= _UA_HANDLER_FRAME;
    switch (ctx->personality(1, action, obj->exception_class, obj, ctx)) {
    case _URC_CONTINUE_UNWIND:
      break;
    case _URC_INSTALL_CONTEXT:
      unw_resume(ctx); // Return if there is an error
      return _URC_FATAL_PHASE2_ERROR;
    default: return _URC_FATAL_PHASE2_ERROR; // Unknown result code
    }
  }
  return _URC_FATAL_PHASE2_ERROR;
}
```

Personality

- Bridge between Level 1 Base ABI and Level 2 C++ ABI
- In C++, usually `__gxx_personality_v0` (sjlj: `__gxx_personality_sj0`)
- GCC `libstdc++-v3/libsupc++/eh_personality.cc` and libc++abi, defined in `src/cxa_personality.cpp`
- `__gxx_personality_v0` parses the referenced `.gcc_except_table` piece, locates the call-site code range, and executes specified actions (e.g. jump to a label).
- Roughly, the function is partitioned by `try` into multiple code ranges.

.gcc_except_table

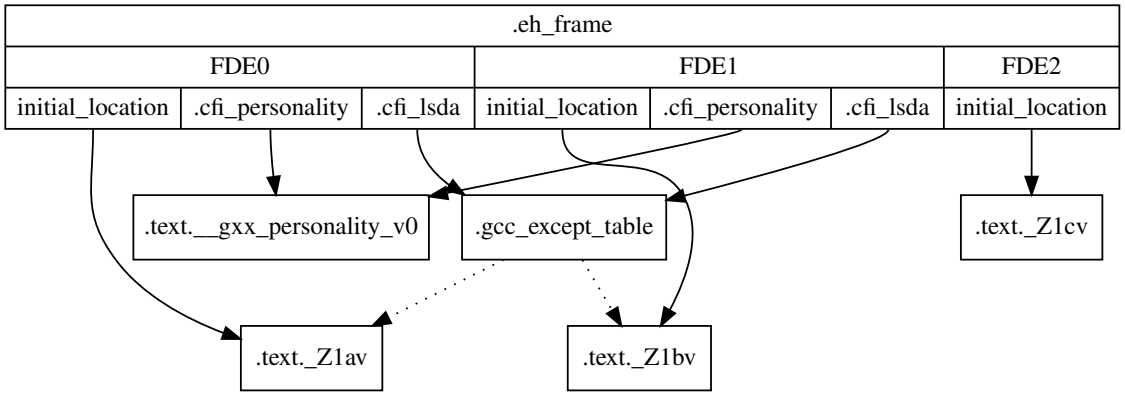
- Interpreted by `__gxx_personality_v0`
- For each code range, describe the landing pad (catch block) and actions (e.g. skip if type mismatch)
- Header + call-site records + action records
- call-site record: call site, landing pad, action record (1 indicates the start)
- action record: type filter, next action record

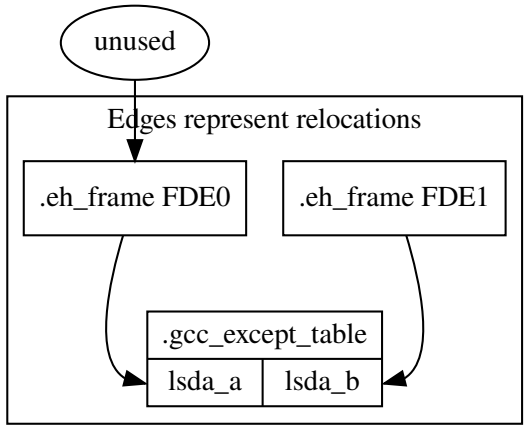
```
main:                                   # @main
.Lfunc_begin0:
  .cfi_startproc
  .cfi_personality 3, __gxx_personality_v0
  .cfi_lsda 3, .Lexception0
# %bb.0:                                # %entry
  pushq   %rax
  .cfi_def_cfa_offset 16
.Ltmp0:
  callq   _Z2fbv                        # try region
.Ltmp1:
.LBB0_2:
  xorl    %eax, %eax
  popq    %rcx
  .cfi_def_cfa_offset 8
  retq
.LBB0_1:                                # landing pad
  .cfi_def_cfa_offset 16
.Ltmp2:
  movq    %rax, %rdi
  callq   __cxa_begin_catch
  movl    (%rax), %esi
  movl    $.L.str, %edi
  xorl    %eax, %eax
  callq   printf
  callq   __cxa_end_catch
  jmp     .LBB0_2
.Lfunc_end0:
  .size   main, .Lfunc_end0-main
  .cfi_endproc
```

```
  .section        .gcc_except_table,"a",@progbits
  .p2align        2
GCC_except_table0:
.Lexception0:
  .byte   255                             # @LPStart Encoding = omit
  .byte   3                               # @TType Encoding = udata4
  .uleb128 .Lttbase0-.Lttbaseref0         # The start of action records
.Lttbaseref0:
  .byte   1                               # Call site Encoding = uleb128
  .uleb128 .Lcst_end0-.Lcst_begin0
.Lcst_begin0:                             # 2 call site code ranges
  .uleb128 .Ltmp0-.Lfunc_begin0           # >> Call Site 1 <<
  .uleb128 .Ltmp1-.Ltmp0                  #   Call between .Ltmp0 and .Ltmp1
  .uleb128 .Ltmp2-.Lfunc_begin0           #     jumps to .Ltmp2
  .byte   1                               #   On action: 1
  .uleb128 .Ltmp1-.Lfunc_begin0           # >> Call Site 2 <<
  .uleb128 .Lfunc_end0-.Ltmp1             #   Call between .Ltmp1 and .Lfunc_end0
  .byte   0                               #     has no landing pad
  .byte   0                               #   On action: cleanup
.Lcst_end0:
  .byte   1                               # >> Action Record 1 <<
                                  #   Catch TypeInfo 1
  .byte   0                               #   No further actions
  .p2align        2
                                  # >> Catch TypeInfos <<
  .long   _ZTIi                           # TypeInfo 1
.Lttbase0:
```

Monolithic .gcc_except_table

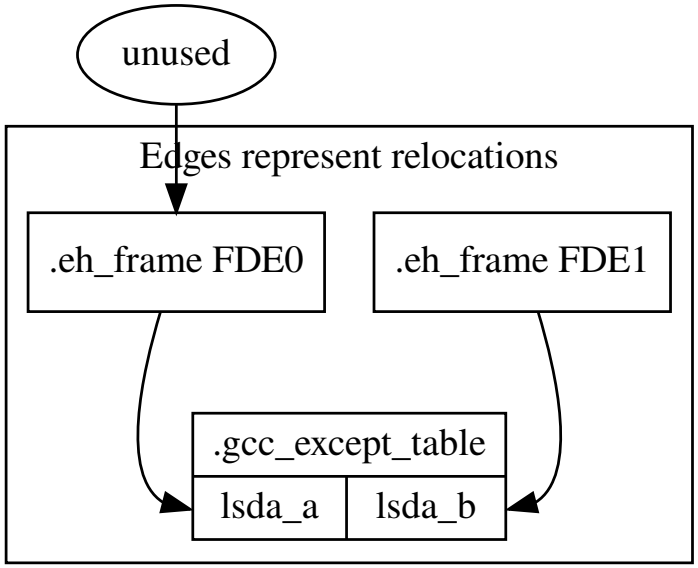
- As of Clang 11, there is one monolithic .gcc_except_table
- Linker --gc-sections: input sections are atoms
- Unused .gcc_except_table (the "referenced" .text sections are discarded) cannot be discarded

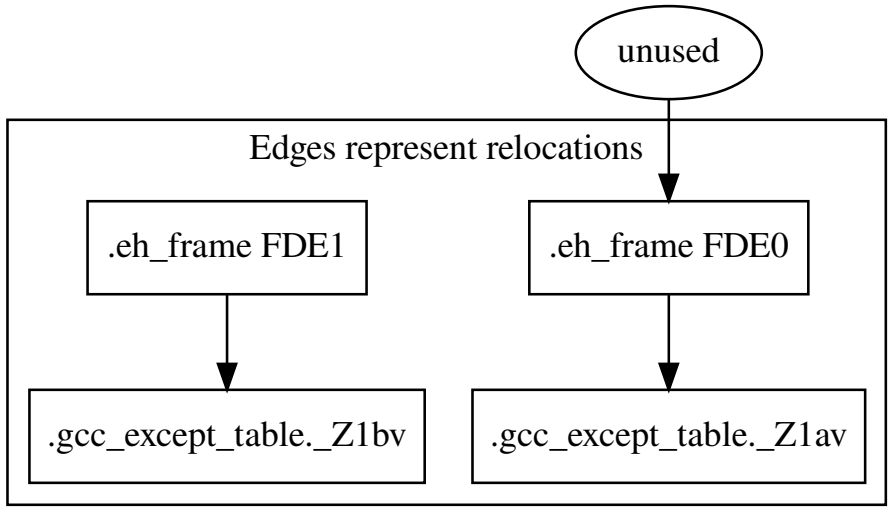




Fragmented .gcc_except_table

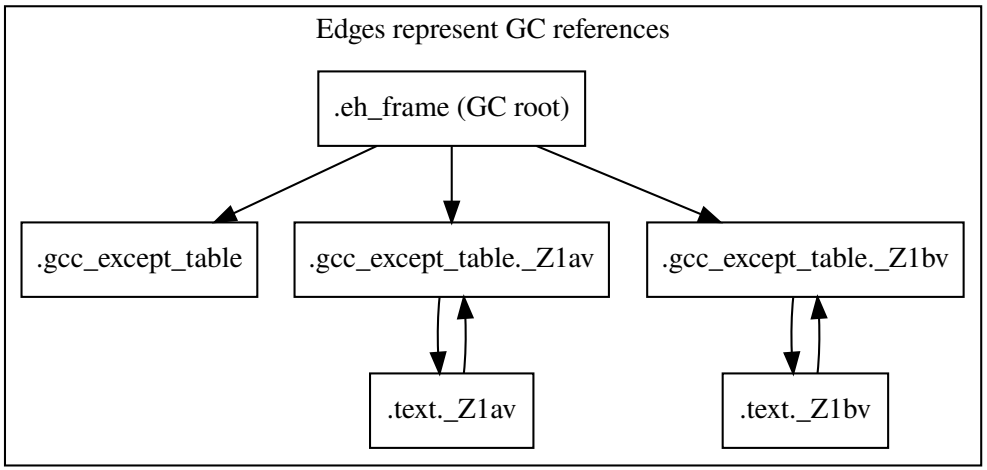
- https://reviews.llvm.org/D83655: Split up .gcc_except_table





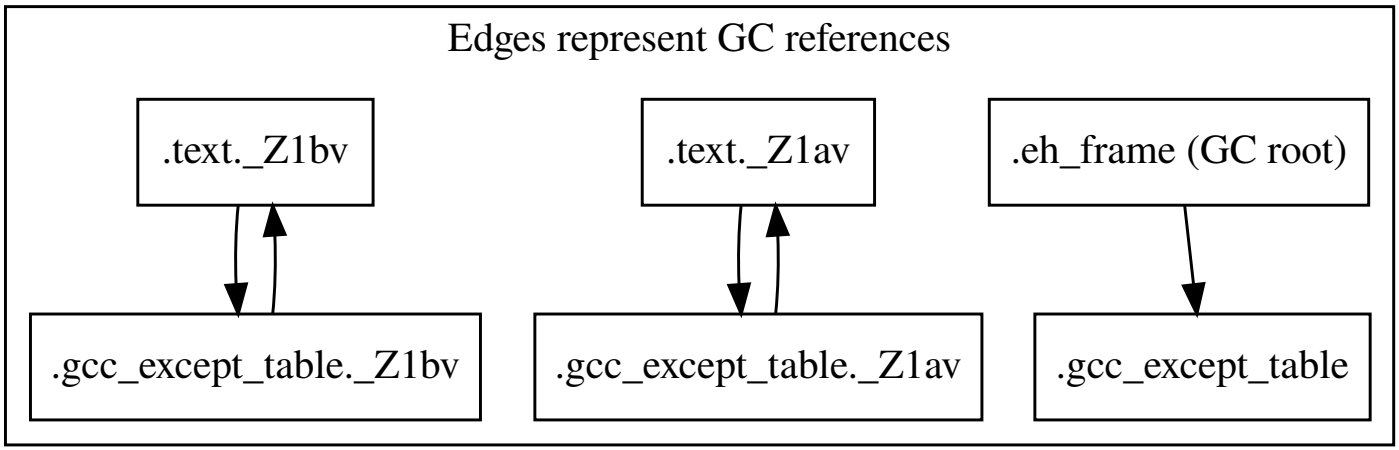
Is that so simple?

- No! `.text.*` in COMDAT groups cannot be GCed with fragmented `.gcc_except_table.*` (code size increase)
- LLD handles `--gc-sections` before GCing `.eh_frame`
- During GC, all pieces in `.eh_frame` are live (GC root). They mark all `.gcc_except_table.*` live
- A `.gcc_except_table.*` marks other members (`.text.*`) in the same group live (linker rule)



Let's fix LLD!

- `https://reviews.llvm.org/D91579`: for `.eh_frame`, don't mark `.gcc_except_table` within a COMDAT group



Future work

- Clang `.gcc_except_table` is inefficient for pass-through purposes. GCC produces header-only LSDA (4 bytes).
- Clang/LLD interop: garbage collect unused `.gcc_except_table` not within COMDAT groups
- Efficient (space/performance) `.eh_frame` (very difficult; (current) compact unwinding has lots of limitations; `https://maskray.me/blog/2020-11-08-stack-unwinding`)