Function Multi Versioning for AArch64: Compiler aided function specialization with runtime dispatch

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Intro

The problem

- Software is deployed on various devices (we may compile for a baseline and reuse the binaries).
- Most CPUs implement optional instructions which may not be present on the target of compilation.
- For example, on Arm, dotproduct instructions may not be available.
- To make use of such instructions, a run-time check is needed.

The solution

Function Multi Versioning (FMV)
https://learn.arm.com/learning-paths/cross-platform/function-multiversioning

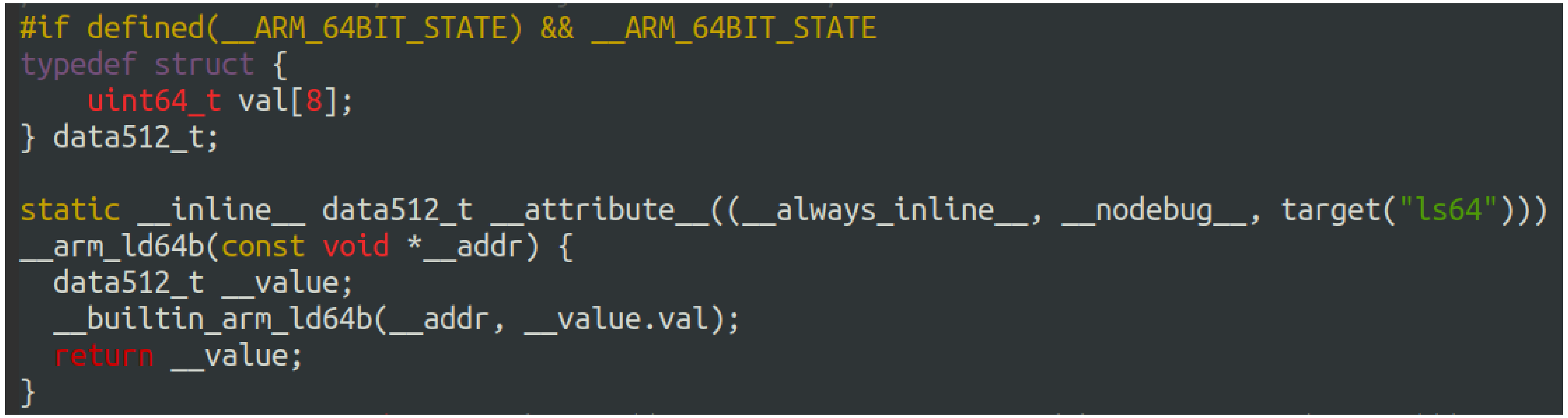
- lets the compiler generate multiple function versions, and
- auto-dispatch between them

What’s new?

- FMV was originally developed for x86 using the function attributes ***target*** and ***target_clones***
  - https://llvm.org/devmtg/2014-10/#talk22 `__attribute__((target("sse4.2")))`
  - https://reviews.llvm.org/D40819

- On AArch64 the ***target*** attribute is broadly used as an optimization hint,
  - for example in header files of Arm C Language Extensions:

lib/clang/21/include/arm_acle.h



```
#if defined(__ARM_64BIT_STATE) && __ARM_64BIT_STATE
typedef struct {
    uint64_t val[8];
} data512_t;

static __inline__ data512_t __attribute__((__always_inline__, __nodebug__, target("ls64")))
__arm_ld64b(const void *__addr) {
  data512_t __value;
  __builtin_arm_ld64b(__addr, __value.val);
  return __value;
}
```

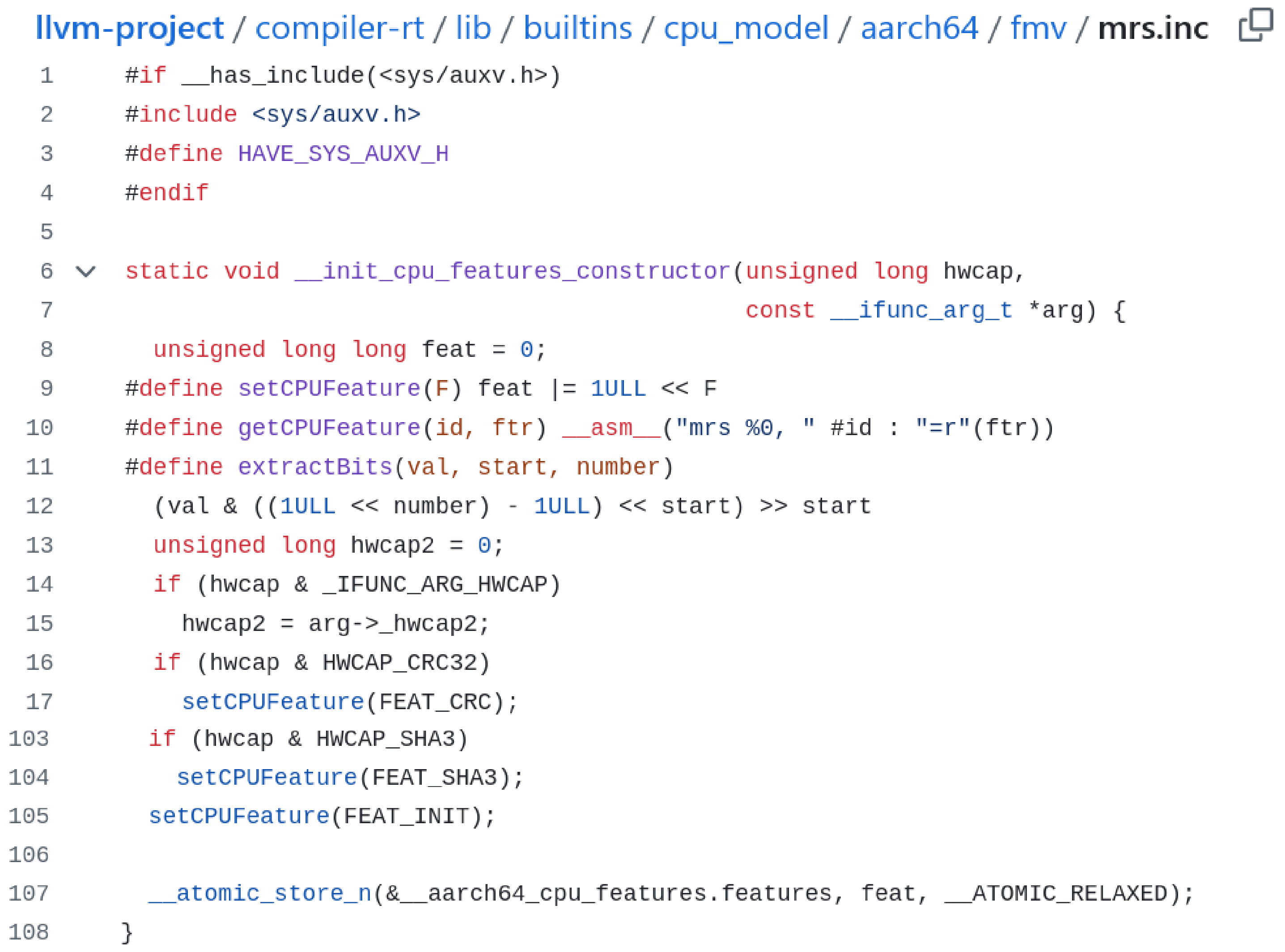
- Therefore, we introduced a new attribute ***target_version*** (also adopted by RISC-V) and wrote a specification for FMV in ACLE (currently beta).

Clang CodeGen

- Clang generates multiple function versions with ***mangled names*** as per https://arm-software.github.io/acle/main/acle.html#name-mangling
  - each version may use several features, their names are encoded in the mangled name
  - `__attribute((target_version("crc+bti+aes+bf16"))) int fmv(void);` → `@fmv._MaesMbf16MbtiMcrc()`
- Each version is associated with ***metadata*** which propagate information from C/C++ source to LLVM.
- Clang generates a ***resolver function*** that determines which version to run when the function is called.
  - The resolution is dynamic (it is performed at load time) and permanent for the lifetime of the process.
  - The resolver: (1) initializes the runtime, (2) detects features, and (3) selects the available version of highest priority as indicated by https://arm-software.github.io/acle/main/acle.html#mapping
- Clang generates a global ***__aarch64_cpu_features*** which contains the feature bits for runtime detection.

Compiler-rt

The runtime asks the kernel which features are available on host and initializes *__aarch64_cpu_features*



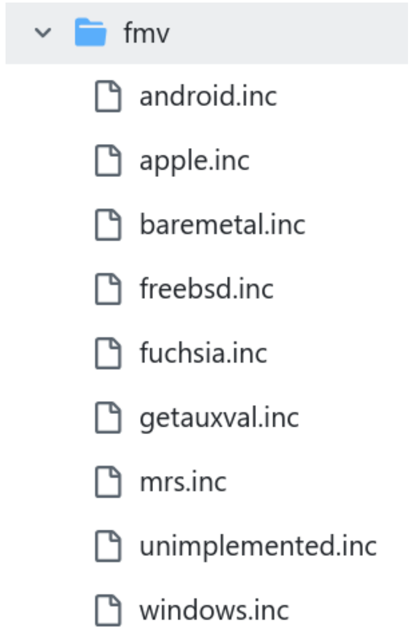
llvm-project / compiler-rt / lib / builtins / cpu_model / aarch64 / fmv / **mrs.inc**

```
#if __has_include(<sys/auxv.h>)
#include <sys/auxv.h>
#define HAVE_SYS_AUXV_H
#endif

static void __init_cpu_features_constructor(unsigned long hwcap,
                                            const __ifunc_arg_t *arg) {
  unsigned long long feat = 0;
#define setCPUFeature(F) feat |= 1ULL << F
#define getCPUFeature(id, ftr) __asm__("mrs %0, " #id : "=r"(ftr))
#define extractBits(val, start, number)
  (val & ((1ULL << number) - 1ULL) << start) >> start
  unsigned long hwcap2 = 0;
  if (hwcap & _IFUNC_ARG_HWCAP)
    hwcap2 = arg->_hwcap2;
  if (hwcap & HWCAP_CRC32)
    setCPUFeature(FEAT_CRC);
  if (hwcap & HWCAP_SHA3)
    setCPUFeature(FEAT_SHA3);
  setCPUFeature(FEAT_INIT);

  __atomic_store_n(&__aarch64_cpu_features.features, feat, __ATOMIC_RELAXED);
}
```

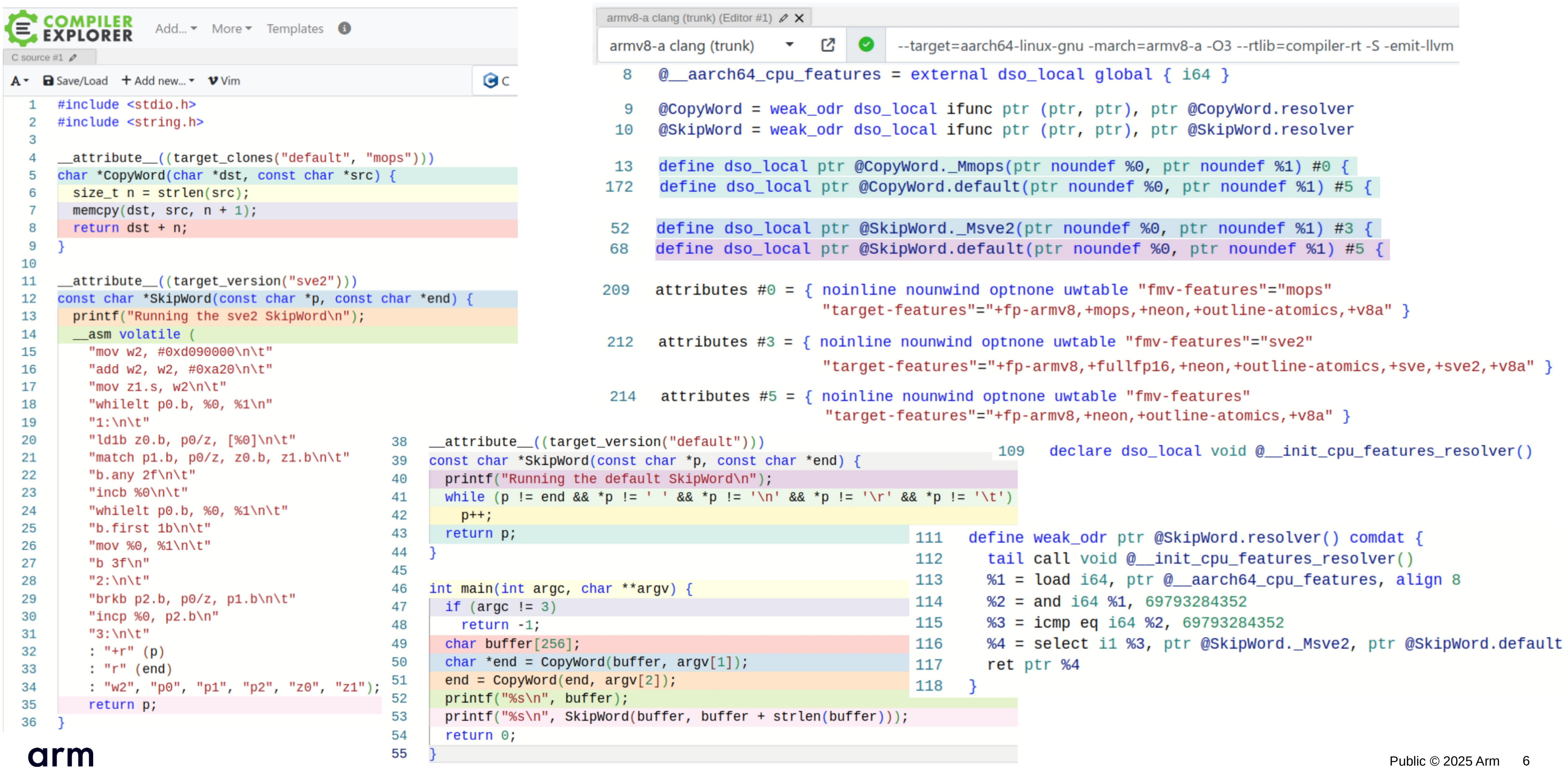
Various platforms are supported



```
fmv
  android.inc
  apple.inc
  baremetal.inc
  freebsd.inc
  fuchsia.inc
  getauxval.inc
  mrs.inc
  unimplemented.inc
  windows.inc
```

Example

https://godbolt.org/z/qsaTohfM7



```c
#include <stdio.h>
#include <string.h>

__attribute__((target_clones("default", "mops")))
char *CopyWord(char *dst, const char *src) {
  size_t n = strlen(src);
  memcpy(dst, src, n + 1);
  return dst + n;
}

__attribute__((target_version("sve2")))
const char *SkipWord(const char *p, const char *end) {
  printf("Running the sve2 SkipWord\n");
  __asm volatile (
    "mov w2, #0xd090000\n\t"
    "add w2, w2, #0xa20\n\t"
    "mov z1.s, w2\n\t"
    "whilelt p0.b, %0, %1\n"
    "1:\n\t"
    "ld1b z0.b, p0/z, [%0]\n\t"
    "match p1.b, p0/z, z0.b, z1.b\n\t"
    "b.any 2f\n\t"
    "incb %0\n\t"
    "whilelt p0.b, %0, %1\n\t"
    "b.first 1b\n\t"
    "mov %0, %1\n\t"
    "b 3f\n"
    "2:\n\t"
    "brkb p2.b, p0/z, p1.b\n\t"
    "incp %0, p2.b\n"
    "3:\n\t"
    : "+r" (p)
    : "r" (end)
    : "w2", "p0", "p1", "p2", "z0", "z1");
    return p;
}
```

```c
__attribute__((target_version("default")))
const char *SkipWord(const char *p, const char *end) {
  printf("Running the default SkipWord\n");
  while (p != end && *p != ' ' && *p != '\n' && *p != '\r' && *p != '\t')
    p++;
  return p;
}

int main(int argc, char **argv) {
  if (argc != 3)
    return -1;
  char buffer[256];
  char *end = CopyWord(buffer, argv[1]);
  end = CopyWord(end, argv[2]);
  printf("%s\n", buffer);
  printf("%s\n", SkipWord(buffer, buffer + strlen(buffer)));
  return 0;
}
```

```
--target=aarch64-linux-gnu -march=armv8-a -O3 --rtlib=compiler-rt -S -emit-llvm
```

```llvm
@__aarch64_cpu_features = external dso_local global { i64 }

@CopyWord = weak_odr dso_local ifunc ptr (ptr, ptr), ptr @CopyWord.resolver
@SkipWord = weak_odr dso_local ifunc ptr (ptr, ptr), ptr @SkipWord.resolver

define dso_local ptr @CopyWord._Mmops(ptr noundef %0, ptr noundef %1) #0 {
define dso_local ptr @CopyWord.default(ptr noundef %0, ptr noundef %1) #5 {

define dso_local ptr @SkipWord._Msve2(ptr noundef %0, ptr noundef %1) #3 {
define dso_local ptr @SkipWord.default(ptr noundef %0, ptr noundef %1) #5 {

attributes #0 = { noinline nounwind optnone uwtable "fmv-features"="mops"
                  "target-features"="+fp-armv8,+mops,+neon,+outline-atomics,+v8a" }

attributes #3 = { noinline nounwind optnone uwtable "fmv-features"="sve2"
                  "target-features"="+fp-armv8,+fullfp16,+neon,+outline-atomics,+sve,+sve2,+v8a" }

attributes #5 = { noinline nounwind optnone uwtable "fmv-features"
                  "target-features"="+fp-armv8,+neon,+outline-atomics,+v8a" }
```

```llvm
declare dso_local void @__init_cpu_features_resolver()
```

```llvm
define weak_odr ptr @SkipWord.resolver() comdat {
  tail call void @__init_cpu_features_resolver()
  %1 = load i64, ptr @__aarch64_cpu_features, align 8
  %2 = and i64 %1, 69793284352
  %3 = icmp eq i64 %2, 69793284352
  %4 = select i1 %3, ptr @SkipWord._Msve2, ptr @SkipWord.default
  ret ptr %4
}
```

Design choices

Resolver emission

- FMV is supported across multiple translation units.
- The resolver cannot “see” versions beyond the current translation unit.
- Emission options:
  - On use (when the function is called)? → may generate multiple (potentially different) resolvers
    → non deterministic version selection depending on linking order ✖
  - Unique resolver in the TU of the default version
    → deterministic version selection regardless of linking order ✔

Feature detection

- Dependent-on features get detected transitively as indicated by https://arm-software.github.io/acle/main/acle.html#dependencies (for example **sve2**→ **sve** → **fp16** → **fp**)
- Features implied by the command line are not exempt from runtime detection (**simd** → **fp**)
  - For example -march=armv8 implies **simd**

FMV info representation

FMV info is autogenerated using
llvm/utils/TableGen/ArmTargetDefEmitter.cpp
https://github.com/llvm/llvm-project/pull/113281

llvm-project / llvm / include / llvm / TargetParser / **AArch64CPUFeatures.inc**

```
// Function Multi Versioning CPU features.
enum CPUFeatures {
  FEAT_RNG,
  FEAT_FLAGM,
  FEAT_FLAGM2,
  FEAT_FP16FML,
  FEAT_DOTPROD,
  FEAT_SM4,
  FEAT_RDM,
  FEAT_LSE,
  FEAT_FP,
  FEAT_SIMD,
  FEAT_CRC,
  RESERVED_FEAT_SHA1, // previously used and now ABI legacy
  FEAT_SHA2,
```

- ***detection ≠ priority*** because the detection bit is part of the ABI; if a feature is added/removed whose priority falls between existing ones…

llvm-project / llvm / include / llvm / TargetParser / **AArch64TargetParser.h**

```
struct FMVInfo {
  StringRef Name;                // The target_version/target_clones spelling.
  CPUFeatures FeatureBit;        // Index of the bit in the FMV feature bitset.
  FeatPriorities PriorityBit;    // Index of the bit in the FMV priority bitset.
  std::optional<ArchExtKind> ID; // The architecture extension to enable.
```

llvm-project / llvm / include / llvm / TargetParser / **AArch64FeatPriorities.inc**

```
// Function Multi Versioning feature priorities.
enum FeatPriorities {
  PRIOR_RNG,
  PRIOR_FLAGM,
  PRIOR_FLAGM2,
  PRIOR_LSE,
  PRIOR_FP,
```

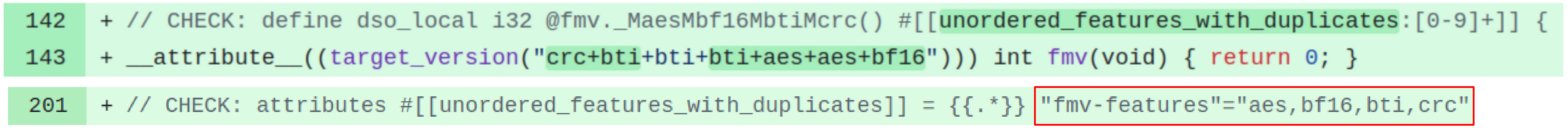
```
// Represents a dependency between two architecture extensions. Later is the
// feature which was added to the architecture after Earlier, and expands the
// functionality provided by it. If Later is enabled, then Earlier will also be
// enabled. If Earlier is disabled, then Later will also be disabled.
struct ExtensionDependency {
  ArchExtKind Earlier;
  ArchExtKind Later;
};
```

- ***dependencies*** are used both for (1) runtime detection, and (2) to enable all the necessary subtarget features for code generation

Metadata in LLVM IR

- https://github.com/llvm/llvm-project/pull/118544
  Similar to ***target-features***.

clang/test/CodeGen/AArch64/fmv-features.c



```
+ // CHECK: define dso_local i32 @fmv._MaesMbf16MbtiMcrc() #[[unordered_features_with_duplicates:[0-9]+]] {
+ __attribute__((target_version("crc+bti+bti+bti+aes+aes+bf16"))) int fmv(void) { return 0; }
```

```
+ // CHECK: attributes #[[unordered_features_with_duplicates]] = {{.*}} "fmv-features"="aes,bf16,bti,crc"
```

Why we need them?

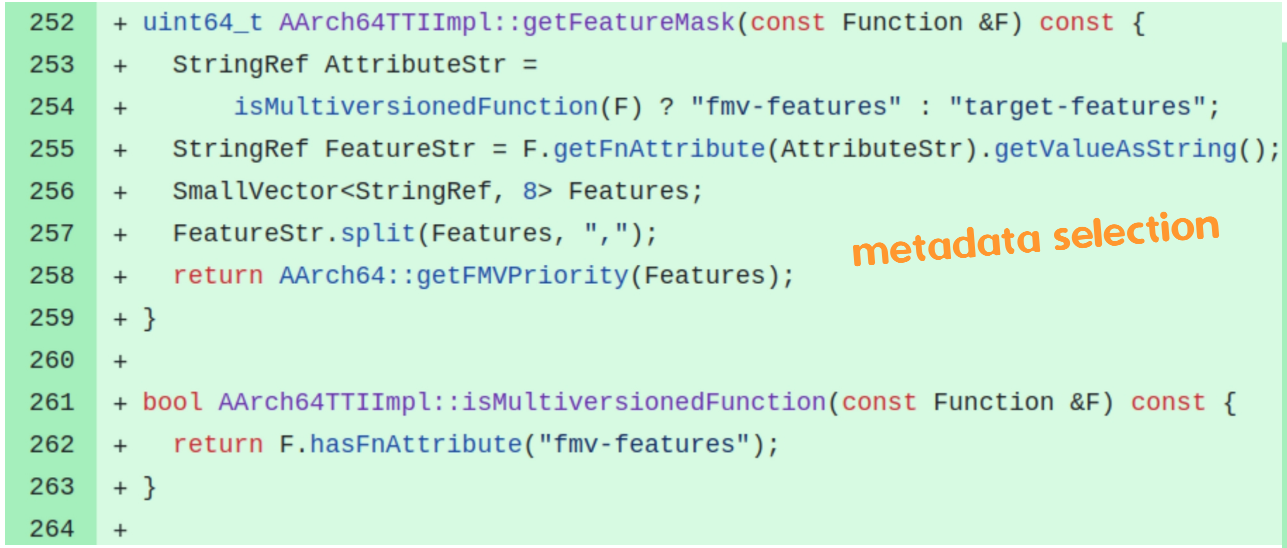
- Suppose you have **target_version("i8mm+dotprod")** and **target_version("fcma").**
- The first version has higher priority because Priority(i8mm) > Priority(fcma) > Priority(dotprod).
- Now suppose you specify **-march=armv8-a+i8mm** on the command line.
- Then the versions would have **target-features** "+dotprod,+i8mm" and "+fcma,+i8mm" respectively.
- If you are using these metadata to deduce version priority, then you would incorrectly deduce that the second version was higher priority than the first!

GlobalOpt

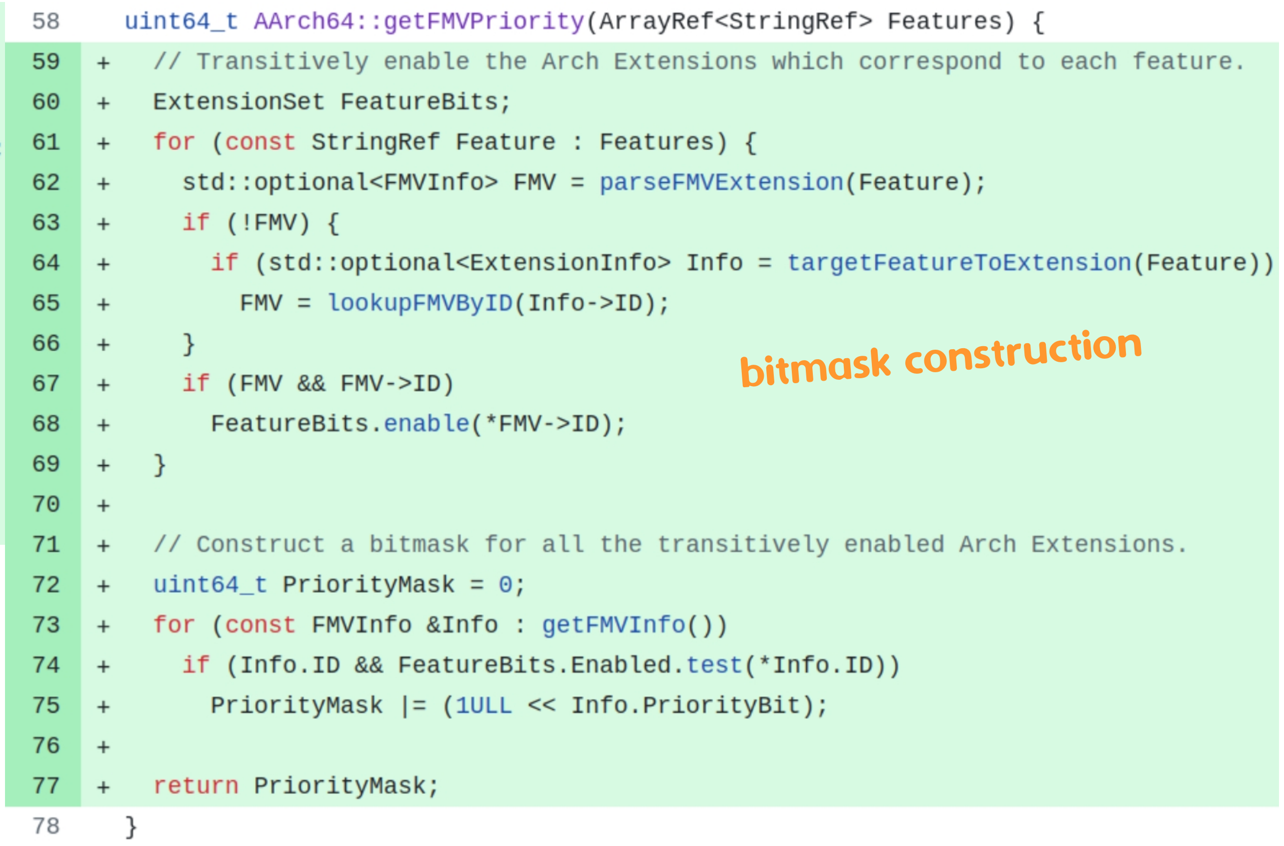
- May statically (at compile time) resolve calls to versioned functions
  https://github.com/llvm/llvm-project/pull/87939

  by comparing LLVM IR metadata between caller and callee.

benefit? → inlining



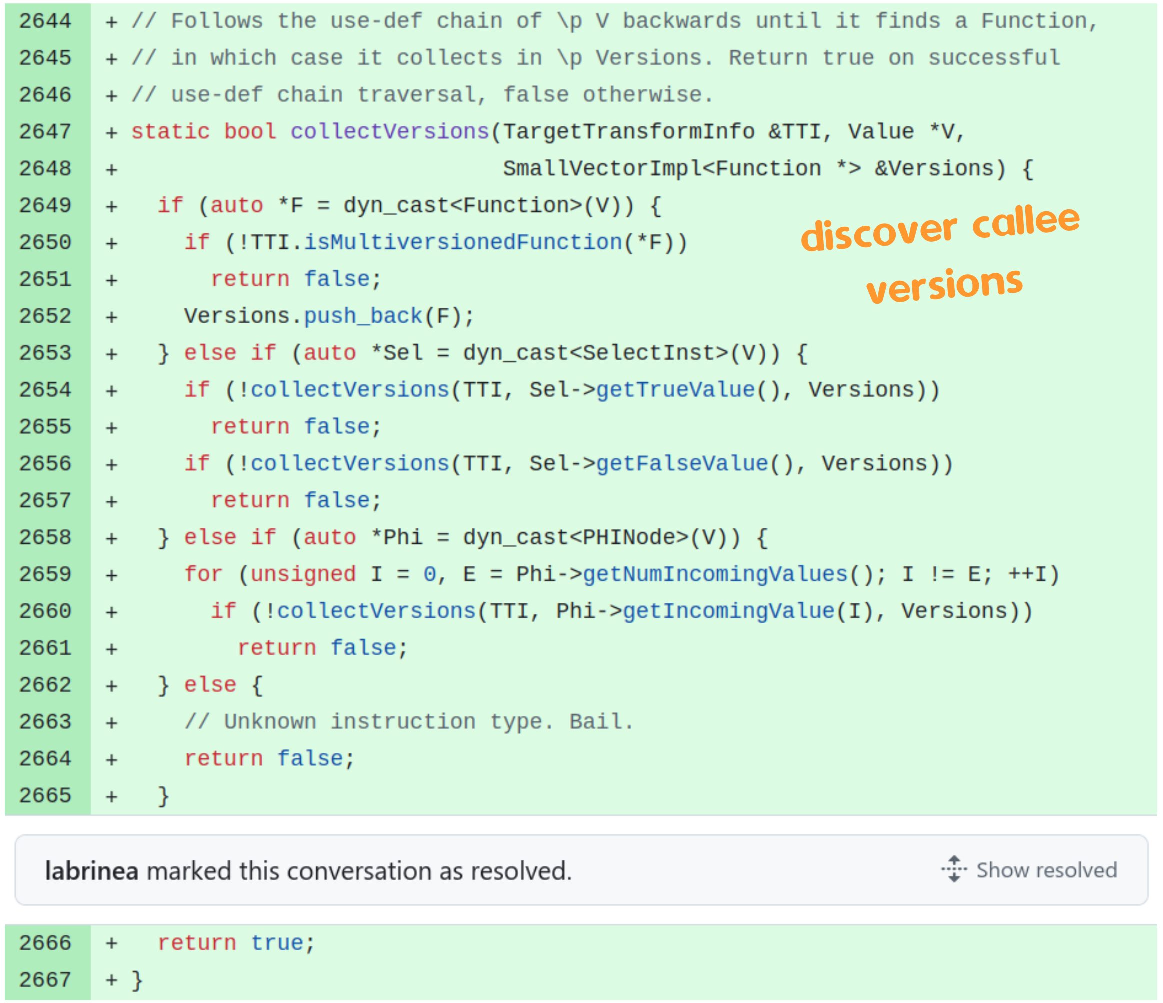
```
+ uint64_t AArch64TTIImpl::getFeatureMask(const Function &F) const {
+   StringRef AttributeStr =
+       isMultiversionedFunction(F) ? "fmv-features" : "target-features";
+   StringRef FeatureStr = F.getFnAttribute(AttributeStr).getValueAsString();
+   SmallVector<StringRef, 8> Features;
+   FeatureStr.split(Features, ",");
+   return AArch64::getFMVPriority(Features);
+ }
+
+ bool AArch64TTIImpl::isMultiversionedFunction(const Function &F) const {
+   return F.hasFnAttribute("fmv-features");
+ }
+
```



```
  uint64_t AArch64::getFMVPriority(ArrayRef<StringRef> Features) {
+   // Transitively enable the Arch Extensions which correspond to each feature.
+   ExtensionSet FeatureBits;
+   for (const StringRef Feature : Features) {
+     std::optional<FMVInfo> FMV = parseFMVExtension(Feature);
+     if (!FMV) {
+       if (std::optional<ExtensionInfo> Info = targetFeatureToExtension(Feature))
+         FMV = lookupFMVByID(Info->ID);
+     }
+     if (FMV && FMV->ID)
+       FeatureBits.enable(*FMV->ID);
+   }
+
+   // Construct a bitmask for all the transitively enabled Arch Extensions.
+   uint64_t PriorityMask = 0;
+   for (const FMVInfo &Info : getFMVInfo())
+     if (Info.ID && FeatureBits.Enabled.test(*Info.ID))
+       PriorityMask |= (1ULL << Info.PriorityBit);
+
+   return PriorityMask;
  }
```

- if FMV caller → FMV callee,
  then compare **fmv-features**
- else if non-FMV caller → FMV callee,
  then compare **target-features** with **fmv-features**

Static resolution algorithm

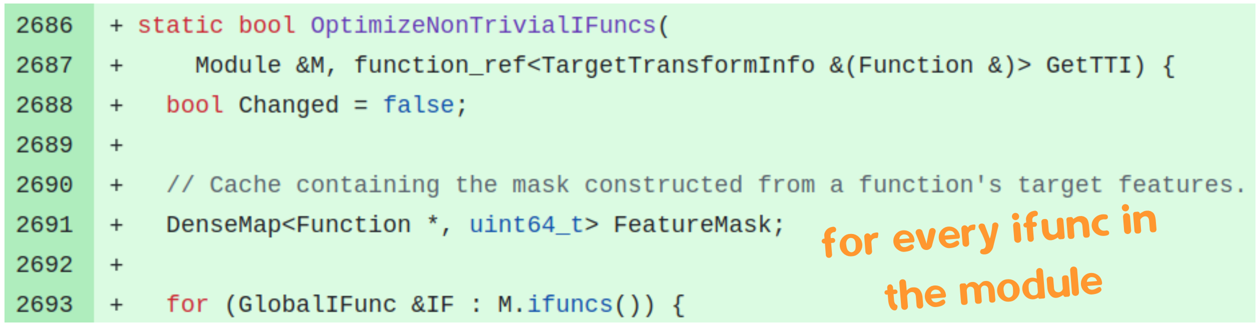


```
+ // Follows the use-def chain of \p V backwards until it finds a Function,
+ // in which case it collects in \p Versions. Return true on successful
+ // use-def chain traversal, false otherwise.
+ static bool collectVersions(TargetTransformInfo &TTI, Value *V,
+                             SmallVectorImpl<Function *> &Versions) {
+   if (auto *F = dyn_cast<Function>(V)) {
+     if (!TTI.isMultiversionedFunction(*F))
+       return false;
+     Versions.push_back(F);
+   } else if (auto *Sel = dyn_cast<SelectInst>(V)) {
+     if (!collectVersions(TTI, Sel->getTrueValue(), Versions))
+       return false;
+     if (!collectVersions(TTI, Sel->getFalseValue(), Versions))
+       return false;
+   } else if (auto *Phi = dyn_cast<PHINode>(V)) {
+     for (unsigned I = 0, E = Phi->getNumIncomingValues(); I != E; ++I)
+       if (!collectVersions(TTI, Phi->getIncomingValue(I), Versions))
+         return false;
+   } else {
+     // Unknown instruction type. Bail.
+     return false;
+   }
```

discover callee versions

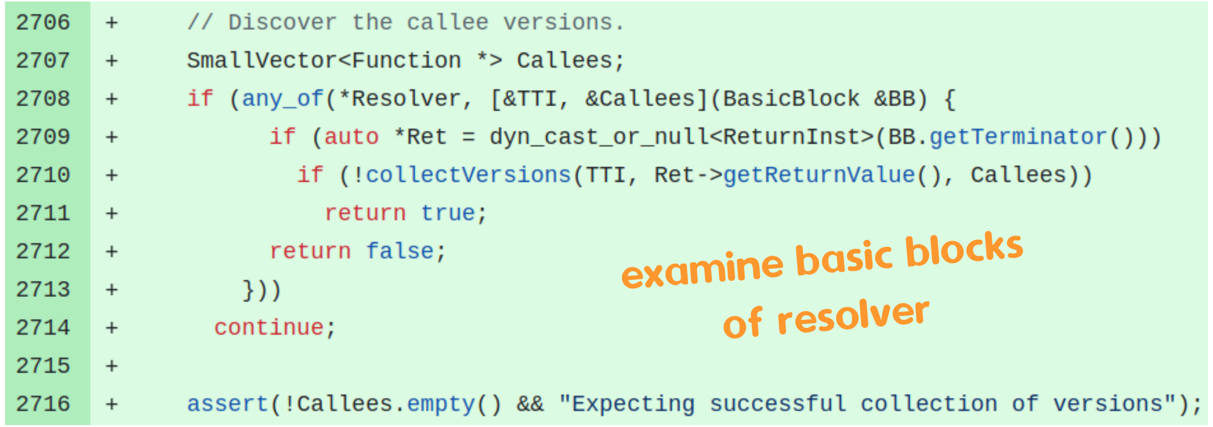
labrinea marked this conversation as resolved. Show resolved

```
+   return true;
+ }
```



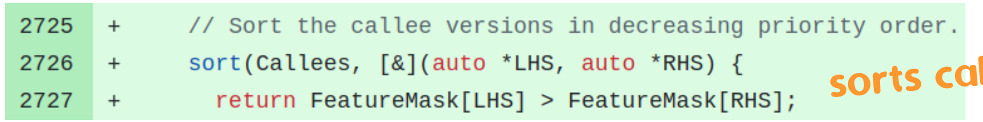
```
+ static bool OptimizeNonTrivialIFuncs(
+     Module &M, function_ref<TargetTransformInfo &(Function &)> GetTTI) {
+   bool Changed = false;
+
+   // Cache containing the mask constructed from a function's target features.
+   DenseMap<Function *, uint64_t> FeatureMask;
+
+   for (GlobalIFunc &IF : M.ifuncs()) {
```

for every ifunc in the module



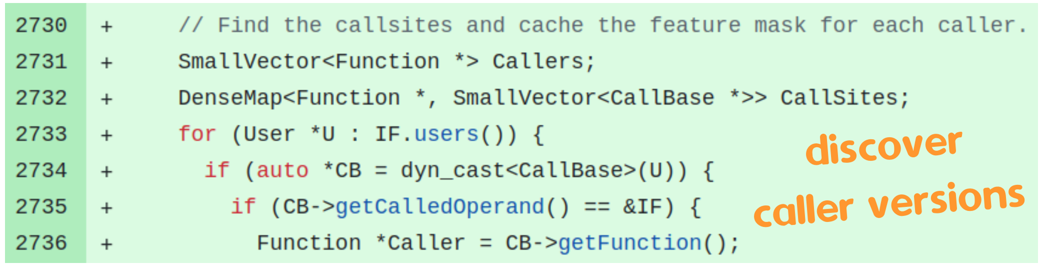
```
+     // Discover the callee versions.
+     SmallVector<Function *> Callees;
+     if (any_of(*Resolver, [&TTI, &Callees](BasicBlock &BB) {
+           if (auto *Ret = dyn_cast_or_null<ReturnInst>(BB.getTerminator()))
+             if (!collectVersions(TTI, Ret->getReturnValue(), Callees))
+               return true;
+           return false;
+         }))
+       continue;
+
+     assert(!Callees.empty() && "Expecting successful collection of versions");
```

examine basic blocks of resolver



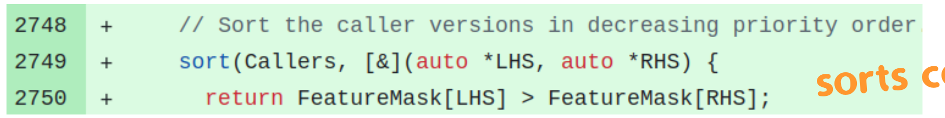
```
+     // Sort the callee versions in decreasing priority order.
+     sort(Callees, [&](auto *LHS, auto *RHS) {
+       return FeatureMask[LHS] > FeatureMask[RHS];
```

sorts callees



```
+     // Find the callsites and cache the feature mask for each caller.
+     SmallVector<Function *> Callers;
+     DenseMap<Function *, SmallVector<CallBase *>> CallSites;
+     for (User *U : IF.users()) {
+       if (auto *CB = dyn_cast<CallBase>(U)) {
+         if (CB->getCalledOperand() == &IF) {
+           Function *Caller = CB->getFunction();
```

discover caller versions

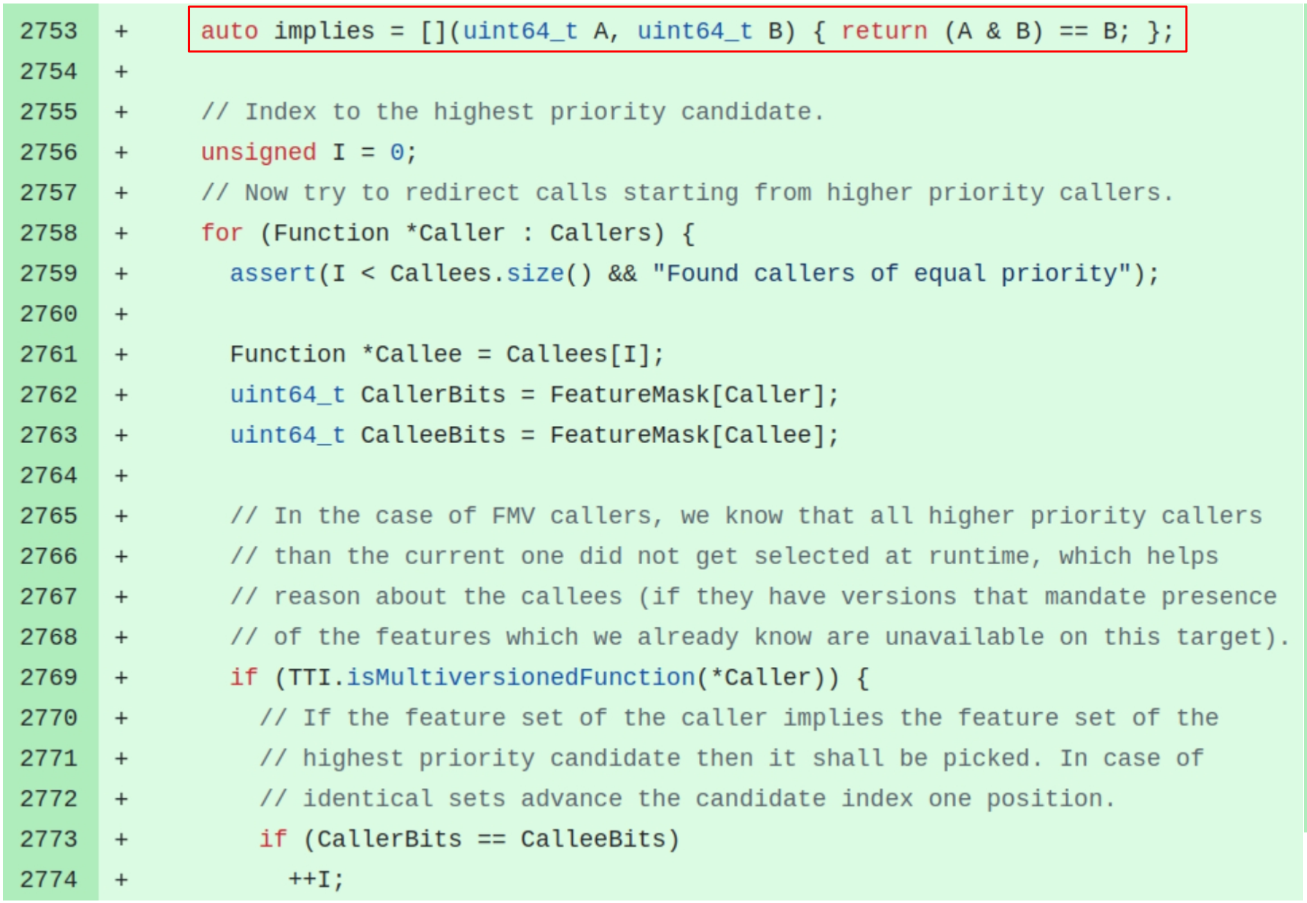


```
+     // Sort the caller versions in decreasing priority order.
+     sort(Callers, [&](auto *LHS, auto *RHS) {
+       return FeatureMask[LHS] > FeatureMask[RHS];
```

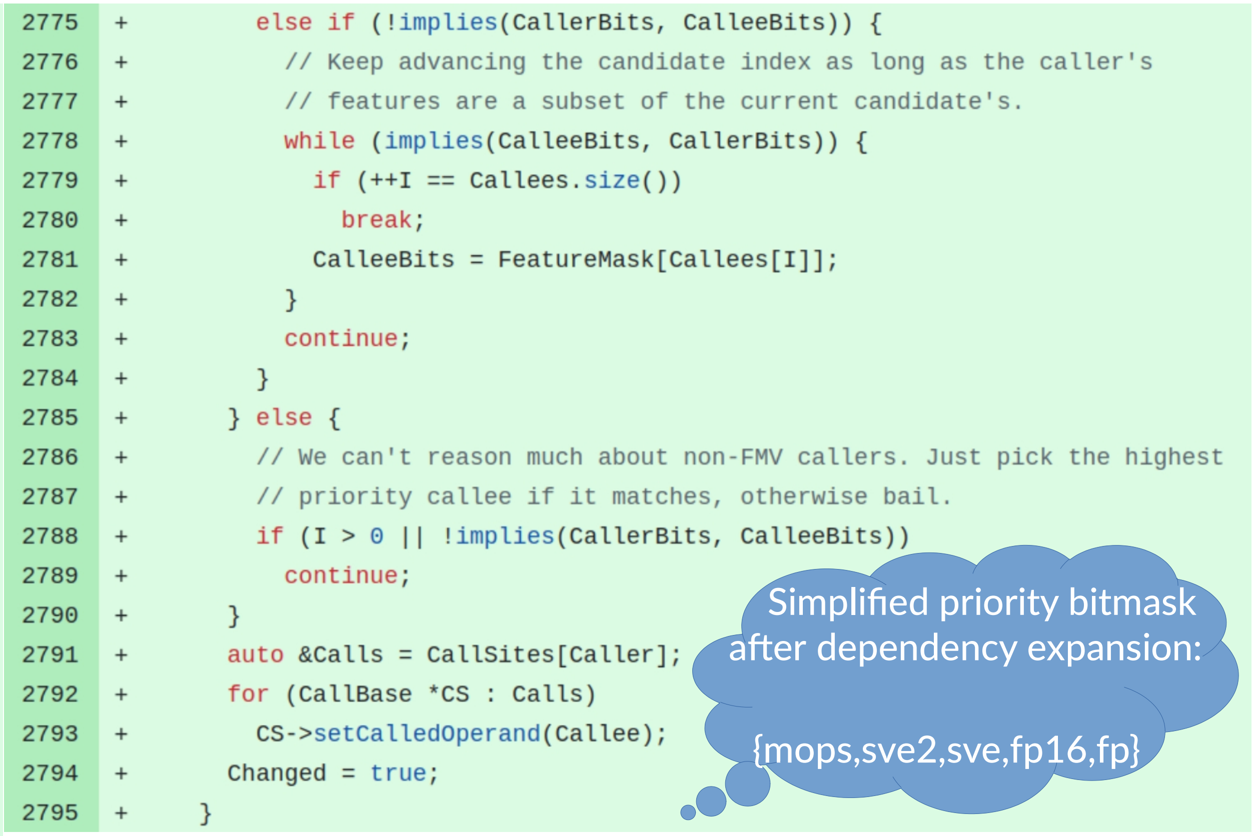
sorts callers

Static resolution algorithm (continued)

Example https://godbolt.org/z/PcGnGbWd3
from llvm/test/Transforms/GlobalOpt/resolve-fmv-ifunc.ll



```
+    auto implies = [](uint64_t A, uint64_t B) { return (A & B) == B; };
+
+    // Index to the highest priority candidate.
+    unsigned I = 0;
+    // Now try to redirect calls starting from higher priority callers.
+    for (Function *Caller : Callers) {
+      assert(I < Callees.size() && "Found callers of equal priority");
+
+      Function *Callee = Callees[I];
+      uint64_t CallerBits = FeatureMask[Caller];
+      uint64_t CalleeBits = FeatureMask[Callee];
+
+      // In the case of FMV callers, we know that all higher priority callers
+      // than the current one did not get selected at runtime, which helps
+      // reason about the callees (if they have versions that mandate presence
+      // of the features which we already know are unavailable on this target).
+      if (TTI.isMultiversionedFunction(*Caller)) {
+        // If the feature set of the caller implies the feature set of the
+        // highest priority candidate then it shall be picked. In case of
+        // identical sets advance the candidate index one position.
+        if (CallerBits == CalleeBits)
+          ++I;
```



```
+        else if (!implies(CallerBits, CalleeBits)) {
+          // Keep advancing the candidate index as long as the caller's
+          // features are a subset of the current candidate's.
+          while (implies(CalleeBits, CallerBits)) {
+            if (++I == Callees.size())
+              break;
+            CalleeBits = FeatureMask[Callees[I]];
+          }
+          continue;
+        }
+      } else {
+        // We can't reason much about non-FMV callers. Just pick the highest
+        // priority callee if it matches, otherwise bail.
+        if (I > 0 || !implies(CallerBits, CalleeBits))
+          continue;
+      }
+      auto &Calls = CallSites[Caller];
+      for (CallBase *CS : Calls)
+        CS->setCalledOperand(Callee);
+      Changed = true;
+    }
```

Simplified priority bitmask after dependency expansion:

{mops,sve2,sve,fp16,fp}

sorted caller versions | **sorted callee versions**

caller._MmopsMsve2 = {1,1,1,1,1} → callee._Mmops = {1,0,0,0,0}
caller._Mmops = {1,0,0,0,0} → callee._Mmops = {1,0,0,0,0}
caller._Msve = {0,0,1,1,1} | callee._Msve2 = {0,1,1,1,1}
caller.default = {0,0,0,0,0} → callee.default = {0,0,0,0,0}
callee._Msve = {0,0,1,1,1}

- mops+sve2 implies mops → we can statically resolve
- mops implies mops → we can statically resolve
  bitmask equality → advance callee iterator
- at this point we know the host does not have mops
  sve does not imply sve2 → we can't statically resolve
  however sve2 implies sve → advance callee iterator
- keep skipping over callee candidates
  sve implies sve → advance callee iterator
- no feature is available → we can statically resolve

arm

Future work

- User can control feature priorities: https://github.com/ARM-software/acle/pull/371
- User can refer to a specific function version: https://github.com/llvm/llvm-project/issues/84094
- Pointer authentication works with IFUNC resolver: https://github.com/llvm/llvm-project/pull/84704
- Request to support more features (like CSSC): https://github.com/llvm/llvm-project/issues/131218
- ? (feedback welcome)

Acknowledgements

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arm

Merci
Danke
Gracias
Grazie
谢谢
ありがとう
Asante
Thank You
감사합니다
धन्यवाद
Kiitos
شكرًا
ধন্যবাদ
תודה
ధన్యవాదములు
Köszönöm

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