Workshop on Essential Abstractions in GCC

GCC Control Flow and Plugins

GCC Resource Center

(www.cse.iitb.ac.in/grc)

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Outline

- Motivation
- Plugins in GCC
- GCC Control Flow
- Link time optimization in GCC
- Conclusions

Part 1

Motivation

Module Binding Mechanisms

- The need for adding, removing, and maintaining modules relatively independently
- The mechanism for supporting this is called by many names:
  - Plugin, hook, callback, ...
  - Sometimes it remains unnamed (eg. compilers in gcc driver)
- It may involve
  - Minor changes in the main source
    Requires static linking
  - No changes in the main source
    Requires dynamic linking

Module Binding Mechanisms

- The need for adding, removing, and maintaining modules relatively independently
- The mechanism for supporting this is called by many names:
  - Plugin, hook, callback, ...
  - Sometimes it remains unnamed (eg. compilers in gcc driver)
- It may involve
  - Minor changes in the main source
    Requires static linking
    We call this a static plugin
  - No changes in the main source
    Requires dynamic linking
    We call this a dynamic plugin

Plugin as a Module Binding Mechanisms

- We view plugin at a more general level than the conventional view
  Adjectives "static" and "dynamic" create a good contrast

- Most often a plugin in a C based software is a data structure containing function pointers and other related information

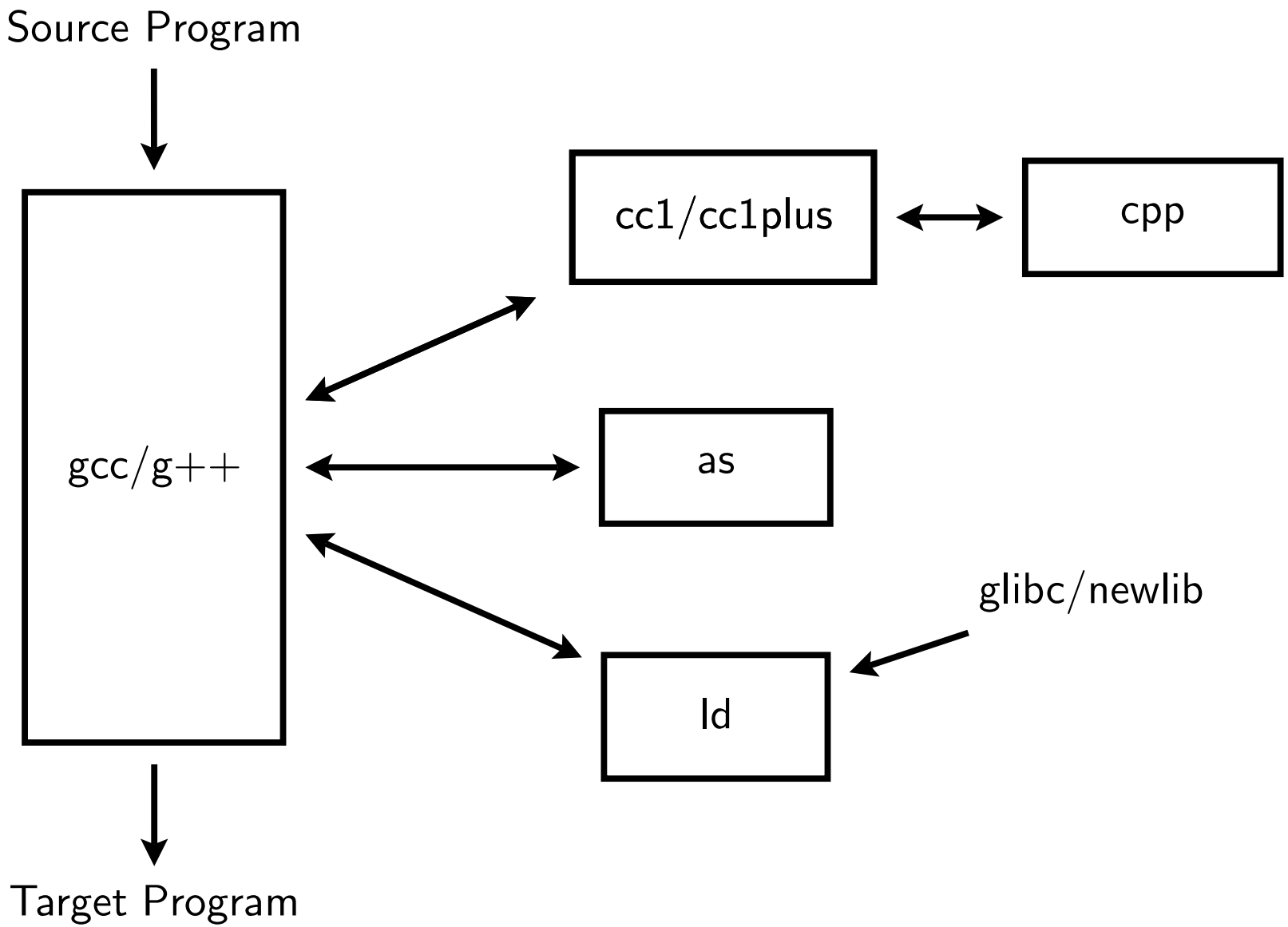
Static Vs. Dynamic Plugins

- Static plugin requires static linking
  - Changes required in `gcc/Makefile.in`, some header and source files
  - At least `cc1` may have to be rebuild
    All files that include the changed headers will have to be recompiled
- Dynamic plugin uses dynamic linking
  - Supported on platforms that support `-ldl -rdynamic`
  - Loaded using `dlopen` and invoked at pre-determined locations in the compilation process
  - Command line option

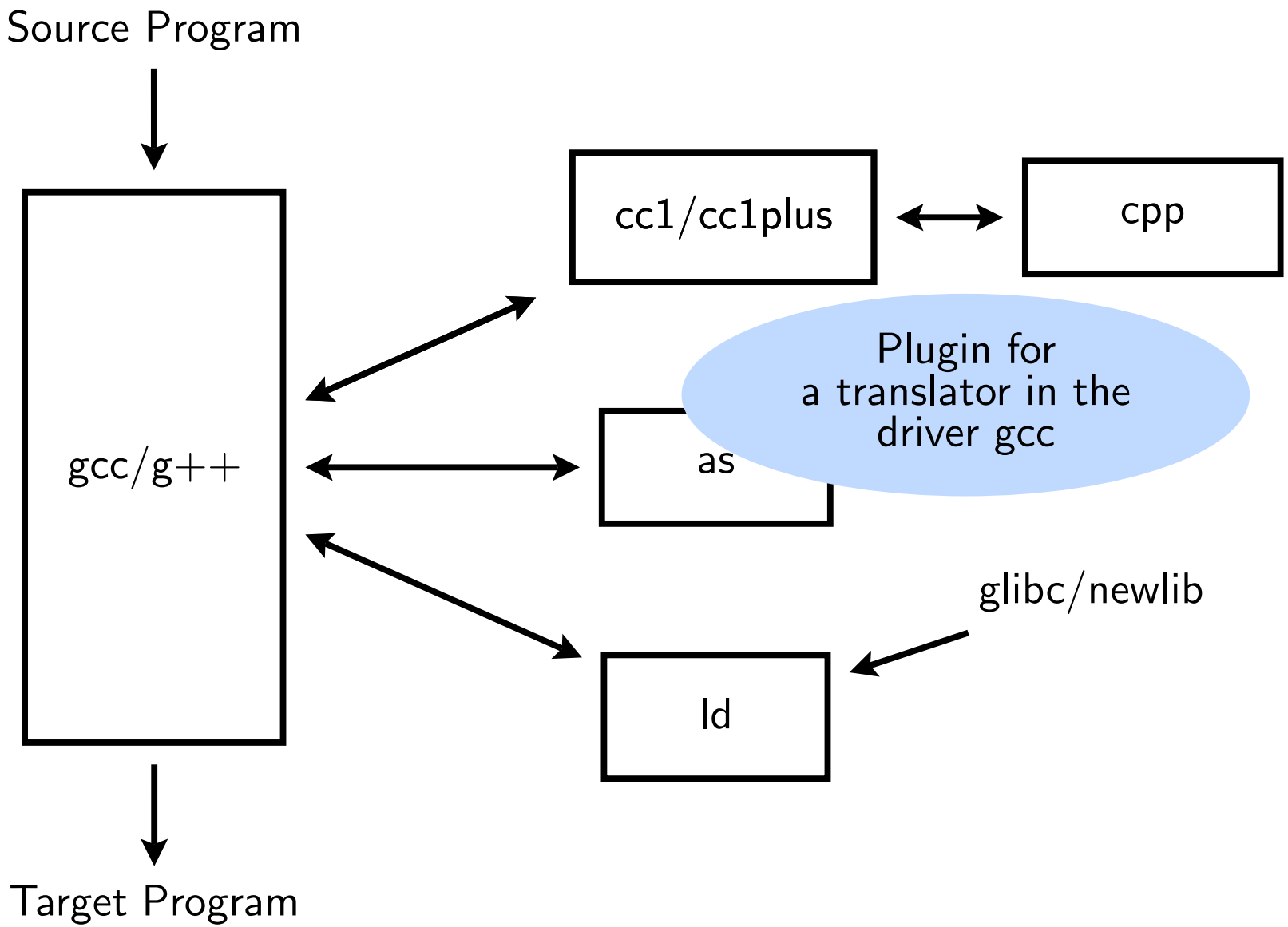
    `-fplugin=/path/to/name.so`

    Arguments required can be supplied as name-value pairs

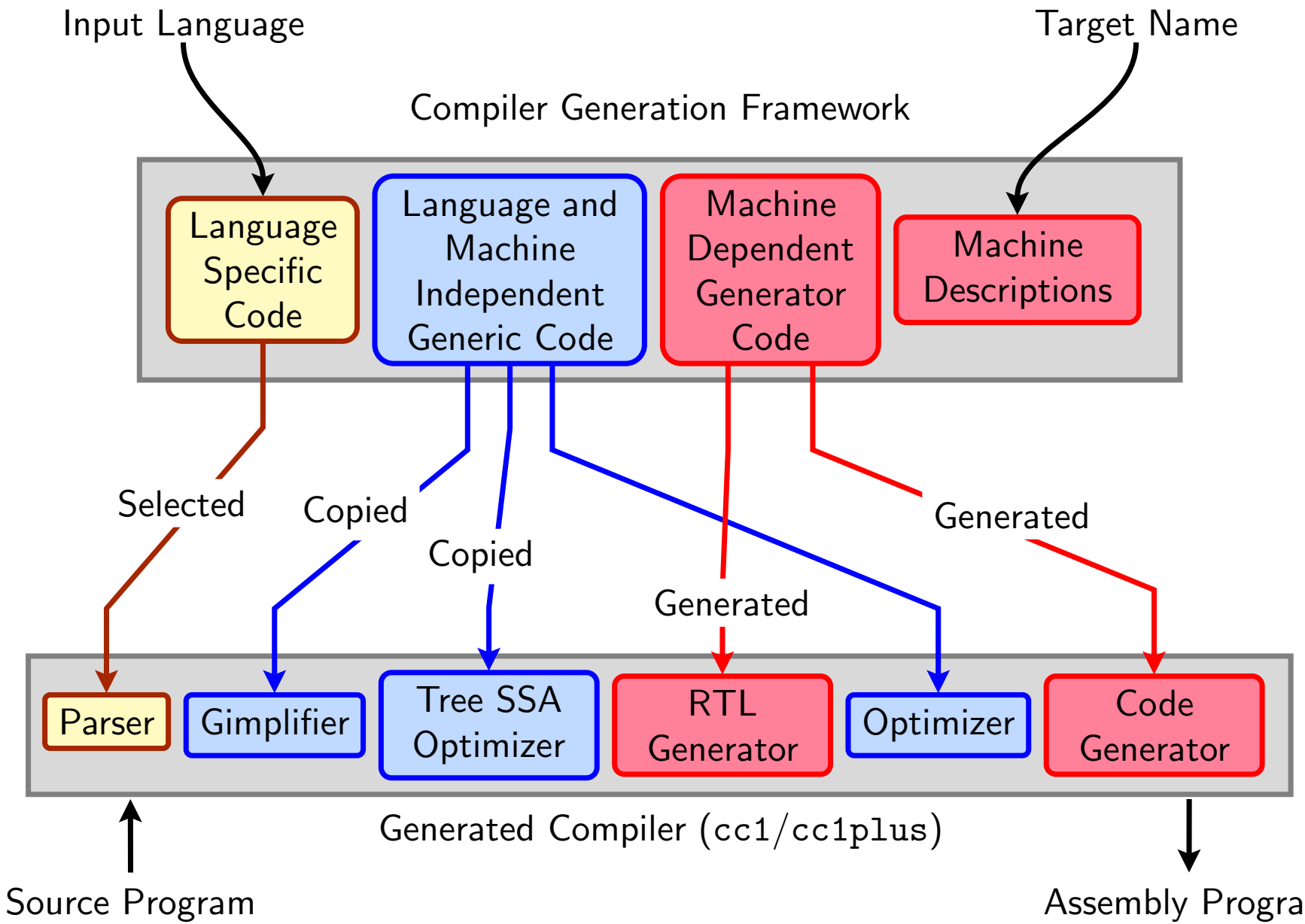
Static Plugins in the GCC Driver



Static Plugins in the GCC Driver



Static Plugins in the Generated Compiler



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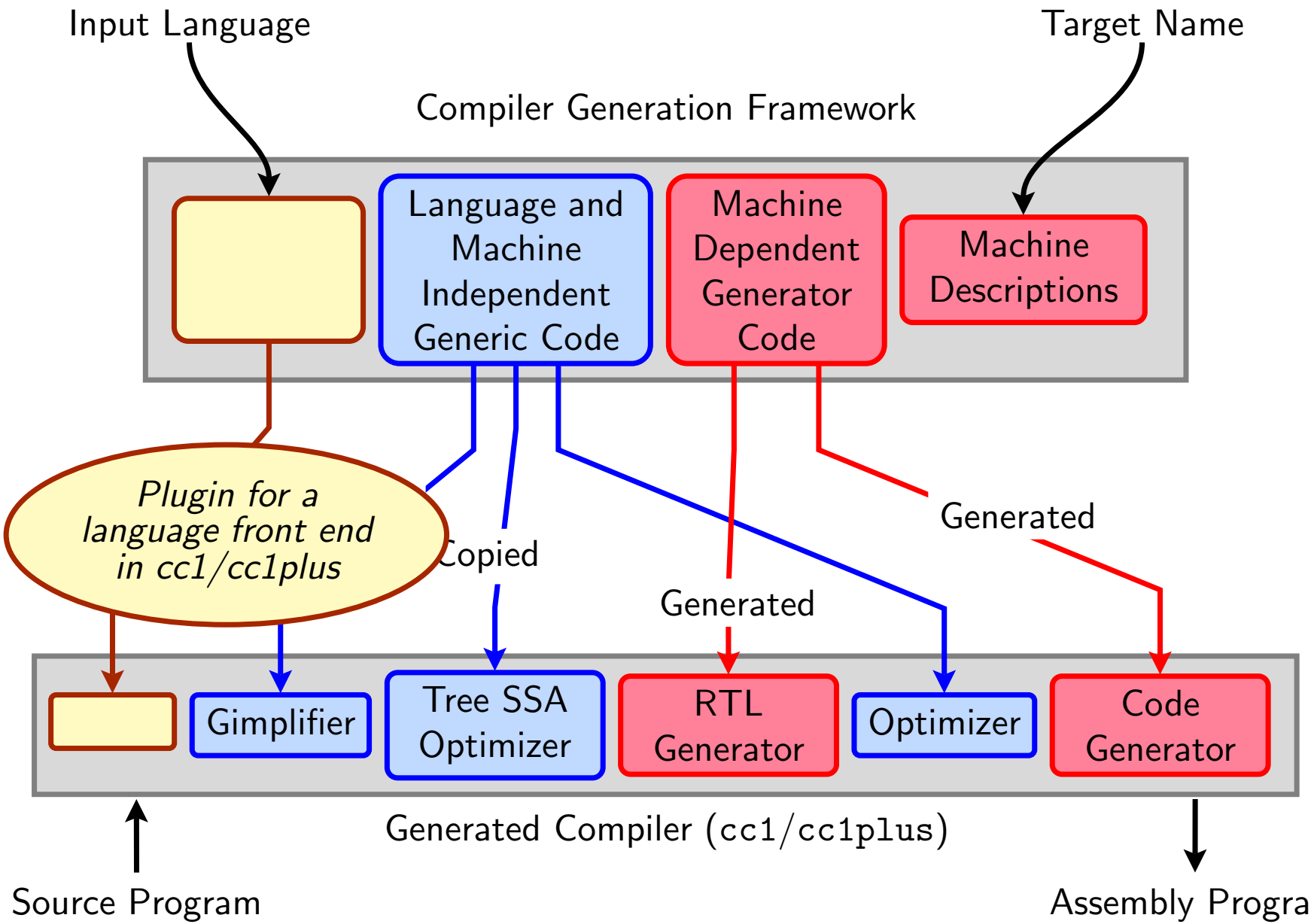

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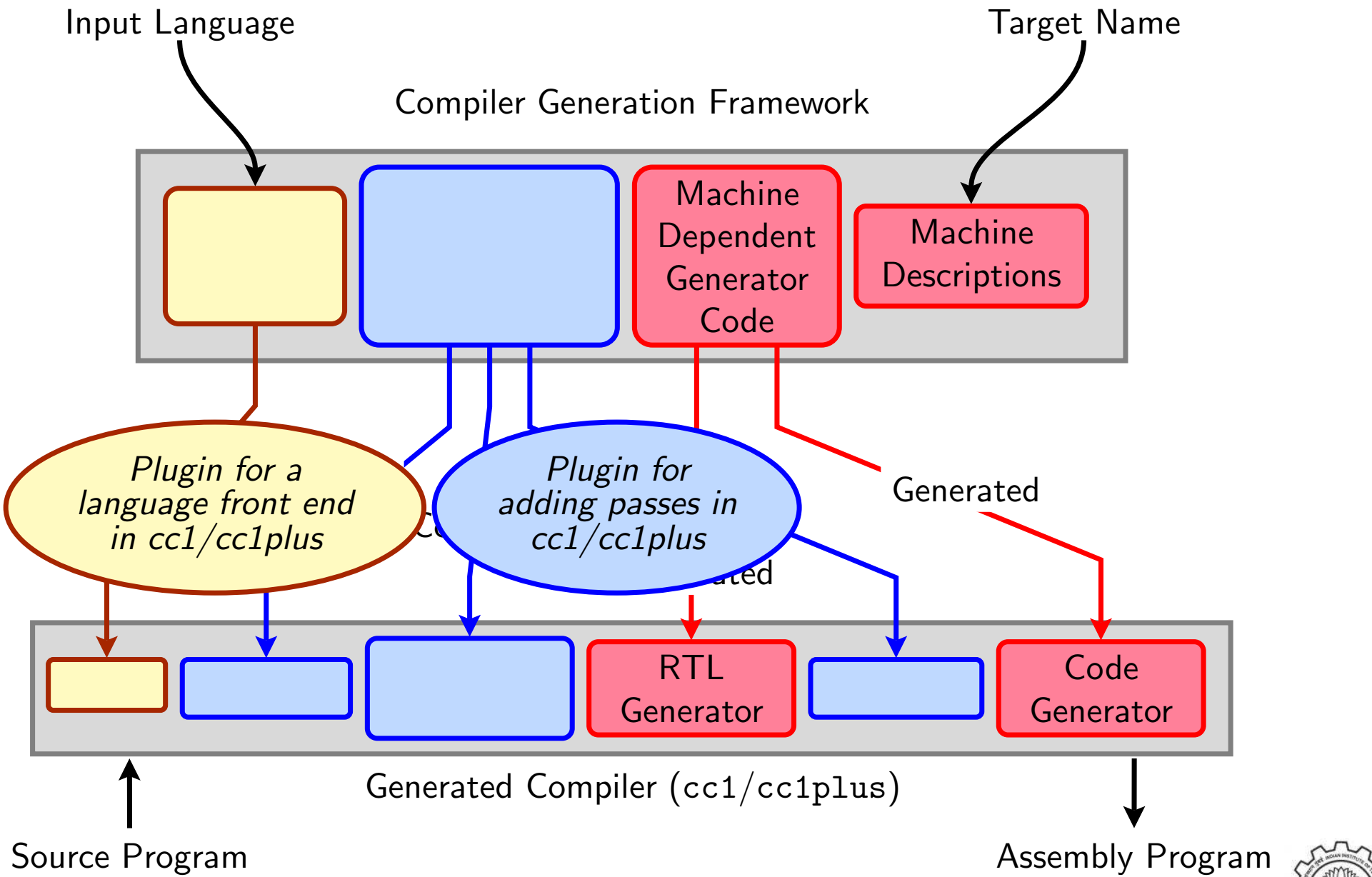

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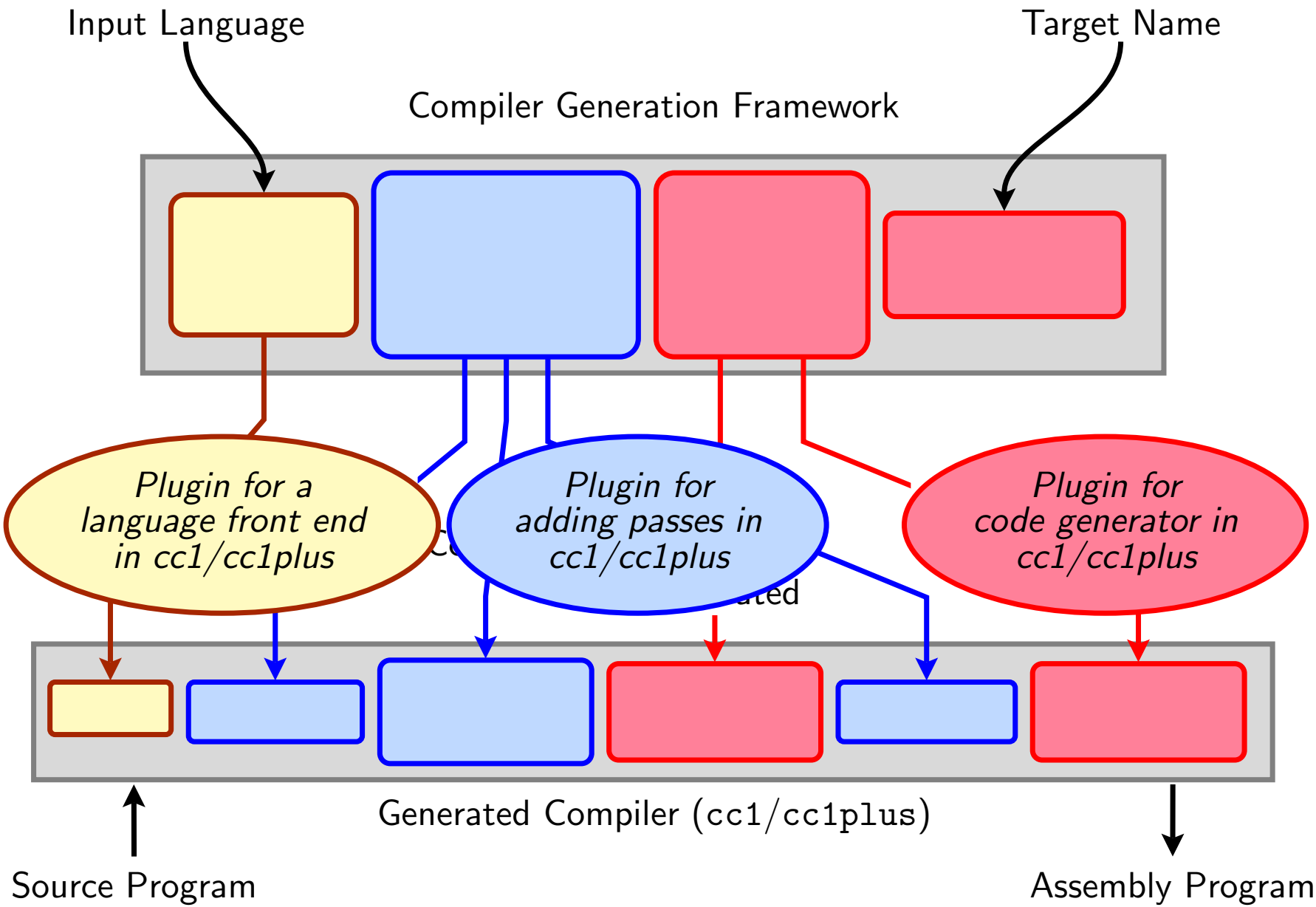


Part 2

Static Plugins in GCC

GCC's Solution

Plugin	Implementation	
	Data Structure	Initialization
Translator in `gcc/g++`	Array of C structures	Development time
Front end in `cc1/cc1plus`	C structure	Build time
Passes in `cc1/cc1plus`	Linked list of C structures	Development time
Back end in `cc1/cc1plus`	Arrays of structures	Build time

Plugin Data Structure in the GCC Driver

```
struct compiler
{
  const char *suffix;      /* Use this compiler for input files
                              whose names end in this suffix.  */

  const char *spec;        /* To use this compiler, run this spec. *

  const char *cpp_spec;    /* If non-NULL, substitute this spec
                              for '%C', rather than the usual
                              cpp_spec.  */
  const int combinable;    /* If nonzero, compiler can deal with
                              multiple source files at once (IMA).
  const int needs_preprocessing;
                           /* If nonzero, source files need to
                              be run through a preprocessor.  */
};
```

Default Specs in the Plugin Data Structure in gcc.c

All entries of Objective C/C++ and some entries of Fortran removed.

```
static const struct compiler default_compilers[] =
{
  {".cc", "#C++", 0, 0, 0},          {".cxx", "#C++", 0, 0, 0},
  {".cpp", "#C++", 0, 0, 0},         {".cp", "#C++", 0, 0, 0},
  {".c++", "#C++", 0, 0, 0},         {".C", "#C++", 0, 0, 0},
  {".CPP", "#C++", 0, 0, 0},         {".ii", "#C++", 0, 0, 0},
  {".ads", "#Ada", 0, 0, 0},         {".adb", "#Ada", 0, 0, 0},
  {".f", "#Fortran", 0, 0, 0},       {".F", "#Fortran", 0, 0, 0},
  {".for", "#Fortran", 0, 0, 0},     {".FOR", "#Fortran", 0, 0, 0},
  {".f90", "#Fortran", 0, 0, 0},     {".F90", "#Fortran", 0, 0, 0},
  {".p", "#Pascal", 0, 0, 0},        {".pas", "#Pascal", 0, 0, 0},
  {".java", "#Java", 0, 0, 0},       {".class", "#Java", 0, 0, 0},
  {".c", "@c", 0, 1, 1},
  {".h", "@c-header", 0, 0, 0},
  {".i", "@cpp-output", 0, 1, 0},
  {".s", "@assembler", 0, 1, 0}
}
```

Default Specs in the Plugin Data Structure in gcc.c

All entries of Objective C/C++ and some entries of Fortran removed.

```
static const struct compiler default_compilers[] =
{
  {".cc", "#C++", 0, 0, 0},          {".cxx", "#C++", 0, 0, 0},
  {".cpp", "#C++", 0, 0, 0},         {".cp", "#C++", 0, 0, 0},
  {".c++", "#C++", 0, 0, 0},         {".C", "#C++", 0, 0, 0},
  {".CPP", "#C++", 0, 0, 0},         {".ii", "#C++", 0, 0, 0},
  {".ads", "#Ada", 0, 0, 0},         {".adb", "#Ada", 0, 0, 0},
  {".f", "#Fortran", 0, 0, 0},       {".F", "#Fortran", 0, 0, 0},
  {".for", "#Fortran", 0, 0, 0},     {".FOR", "#Fortran", 0, 0, 0},
  {".f90", "#Fortran", 0, 0, 0},     {".F90", "#Fortran", 0, 0, 0},
  {".p", "#Pascal", 0, 0, 0},        {".pas", "#Pascal", 0, 0, 0},
  {".java", "#Java", 0, 0, 0},       {".class", "#Java", 0, 0, 0},
  {".c", "@c", 0, 1, 1},
  {".h", "@c-header", 0, 0, 0},
  {".i", "@cpp-output", 0, 1, 0},
  {".s", "@assembler", 0, 1, 0}
}
```

- @: Aliased entry

Default Specs in the Plugin Data Structure in gcc.c

All entries of Objective C/C++ and some entries of Fortran removed.

```
static const struct compiler default_compilers[] =
{
  {".cc", "#C++", 0, 0, 0},          {".cxx", "#C++", 0, 0, 0},
  {".cpp", "#C++", 0, 0, 0},         {".cp", "#C++", 0, 0, 0},
  {".c++", "#C++", 0, 0, 0},         {".C", "#C++", 0, 0, 0},
  {".CPP", "#C++", 0, 0, 0},         {".ii", "#C++", 0, 0, 0},
  {".ads", "#Ada", 0, 0, 0},         {".adb", "#Ada", 0, 0, 0},
  {".f", "#Fortran", 0, 0, 0},       {".F", "#Fortran", 0, 0, 0},
  {".for", "#Fortran", 0, 0, 0},     {".FOR", "#Fortran", 0, 0, 0},
  {".f90", "#Fortran", 0, 0, 0},     {".F90", "#Fortran", 0, 0, 0},
  {".p", "#Pascal", 0, 0, 0},        {".pas", "#Pascal", 0, 0, 0},
  {".java", "#Java", 0, 0, 0},       {".class", "#Java", 0, 0, 0},
  {".c", "@c", 0, 1, 1},
  {".h", "@c-header", 0, 0, 0},
  {".i", "@cpp-output", 0, 1, 0},
  {".s", "@assembler", 0, 1, 0}
}
```

- @: Aliased entry
- #: Default specs not available

Complete Entry for C in gcc.c

```
  {"@c",
   /* cc1 has an integrated ISO C preprocessor.  We should invoke the
      external preprocessor if -save-temps is given.  */
     "%{E|M|MM:%(trad_capable_cpp) %(cpp_options) %(cpp_debug_options)}\
      %{!E:%{!M:%{!MM:\
          %{traditional|ftraditional:\
%eGNU C no longer supports -traditional without -E}\
       %{!combine:\
  %{save-temps|traditional-cpp|no-integrated-cpp:%(trad_capable_cpp) \
%(cpp_options) -o %{save-temps:%b.i} %{!save-temps:%g.i} \n\
    cc1 -fpreprocessed %{save-temps:%b.i} %{!save-temps:%g.i} \
%(cc1_options)}\
  %{!save-temps:%{!traditional-cpp:%{!no-integrated-cpp:\
cc1 %(cpp_unique_options) %(cc1_options)}}}\
          %{!fsyntax-only:%(invoke_as)}} \
      %{combine:\
  %{save-temps|traditional-cpp|no-integrated-cpp:%(trad_capable_cpp) \
%(cpp_options) -o %{save-temps:%b.i} %{!save-temps:%g.i}}\
  %{!save-temps:%{!traditional-cpp:%{!no-integrated-cpp:\
cc1 %(cpp_unique_options) %(cc1_options)}}\
                %{!fsyntax-only:%(invoke_as)}}}}}}", 0, 1, 1},
```

Populated Plugin Data Structure for C++:

gcc/cp/lang-specs.h

```
{".cc",  "@c++", 0, 0, 0},
{".cp",  "@c++", 0, 0, 0},
{".cxx", "@c++", 0, 0, 0},
{".cpp", "@c++", 0, 0, 0},
{".c++", "@c++", 0, 0, 0},
{".C",   "@c++", 0, 0, 0},
{".CPP", "@c++", 0, 0, 0},
{".H",   "@c++-header", 0, 0, 0},
{".hpp", "@c++-header", 0, 0, 0},
{".hp",  "@c++-header", 0, 0, 0},
{".hxx", "@c++-header", 0, 0, 0},
{".h++", "@c++-header", 0, 0, 0},
{".HPP", "@c++-header", 0, 0, 0},
{".tcc", "@c++-header", 0, 0, 0},
{".hh",  "@c++-header", 0, 0, 0},
```

Populated Plugin Data Structure for C++:
gcc/cp/lang-specs.h

```
  {"@c++-header",
    "%{E|M|MM:cc1plus -E %(cpp_options) %2 %(cpp_debug_options)}\
     %{!E:%{!M:%{!MM:\
       %{save-temps|no-integrated-cpp:cc1plus -E\
%(cpp_options) %2 -o %{save-temps:%b.ii} %{!save-temps:%g.ii} \n}\
      cc1plus %{save-temps|no-integrated-cpp:-fpreprocessed %{save-temps:%
      %{!save-temps:%{!no-integrated-cpp:%(cpp_unique_options)}}\
%(cc1_options) %2\
%{!fsyntax-only:%{!fdump-ada-spec*:-o %g.s %{!o*:--output-pch=%i.gch}\
        %W{o*:--output-pch=%*}}%V}}}}",
     CPLUSPLUS_CPP_SPEC, 0, 0},
```


Populated Plugin Data Structure for C++:
gcc/cp/lang-specs.h

```
  {"@c++",
    "%{E|M|MM:cc1plus -E %(cpp_options) %2 %(cpp_debug_options)}\
     %{!E:%{!M:%{!MM:\
       %{save-temps|no-integrated-cpp:cc1plus -E\
%(cpp_options) %2 -o %{save-temps:%b.ii} %{!save-temps:%g.ii} \n}\
      cc1plus %{save-temps|no-integrated-cpp:-fpreprocessed %{save-temps:%
      %{!save-temps:%{!no-integrated-cpp:%(cpp_unique_options)}}\
%(cc1_options) %2\
       %{!fsyntax-only:%(invoke_as)}}}}",
     CPLUSPLUS_CPP_SPEC, 0, 0},
  {".ii", "@c++-cpp-output", 0, 0, 0},

  {"@c++-cpp-output",
   "%{!M:%{!MM:%{!E:\
    cc1plus -fpreprocessed %i %(cc1_options) %2\
    %{!fsyntax-only:%(invoke_as)}}}}", 0, 0, 0},
```

Populated Plugin Data Structure for LTO:

gcc/lto/lang-specs.h

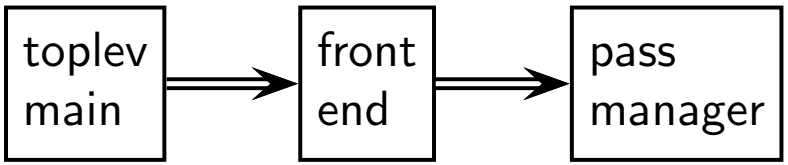
```
/* LTO contributions to the "compilers" array in gcc.c.  */

  {"@lto", "lto1 %(cc1_options) %i %{!fsyntax-only:%(invoke_as)}",
   /*cpp_spec=*/NULL, /*combinable=*/1, /*needs_preprocessing=*/0},
```

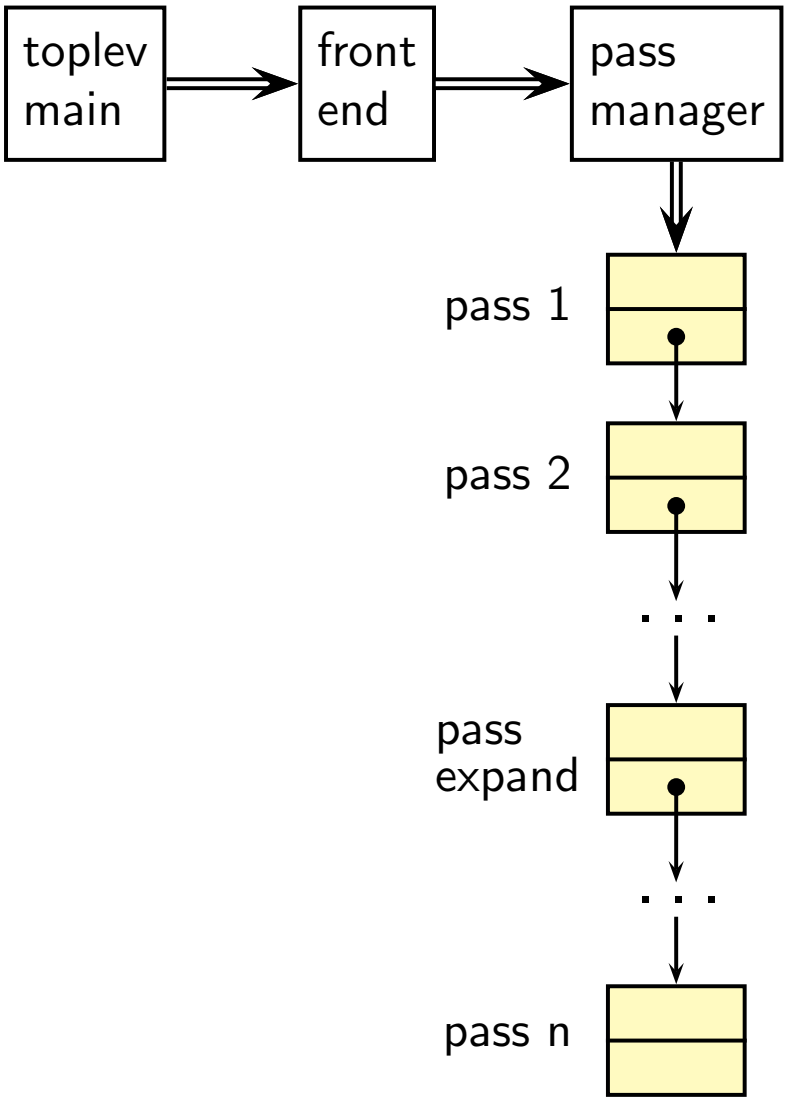

What about the Files to be Procecced by the Linker?

- Linking is the last step
- Every file is passed on to linker unless it is suppressed
- If a translator is not found, input file is assumed to be a file for linker

Plugin Structure in `cc1`



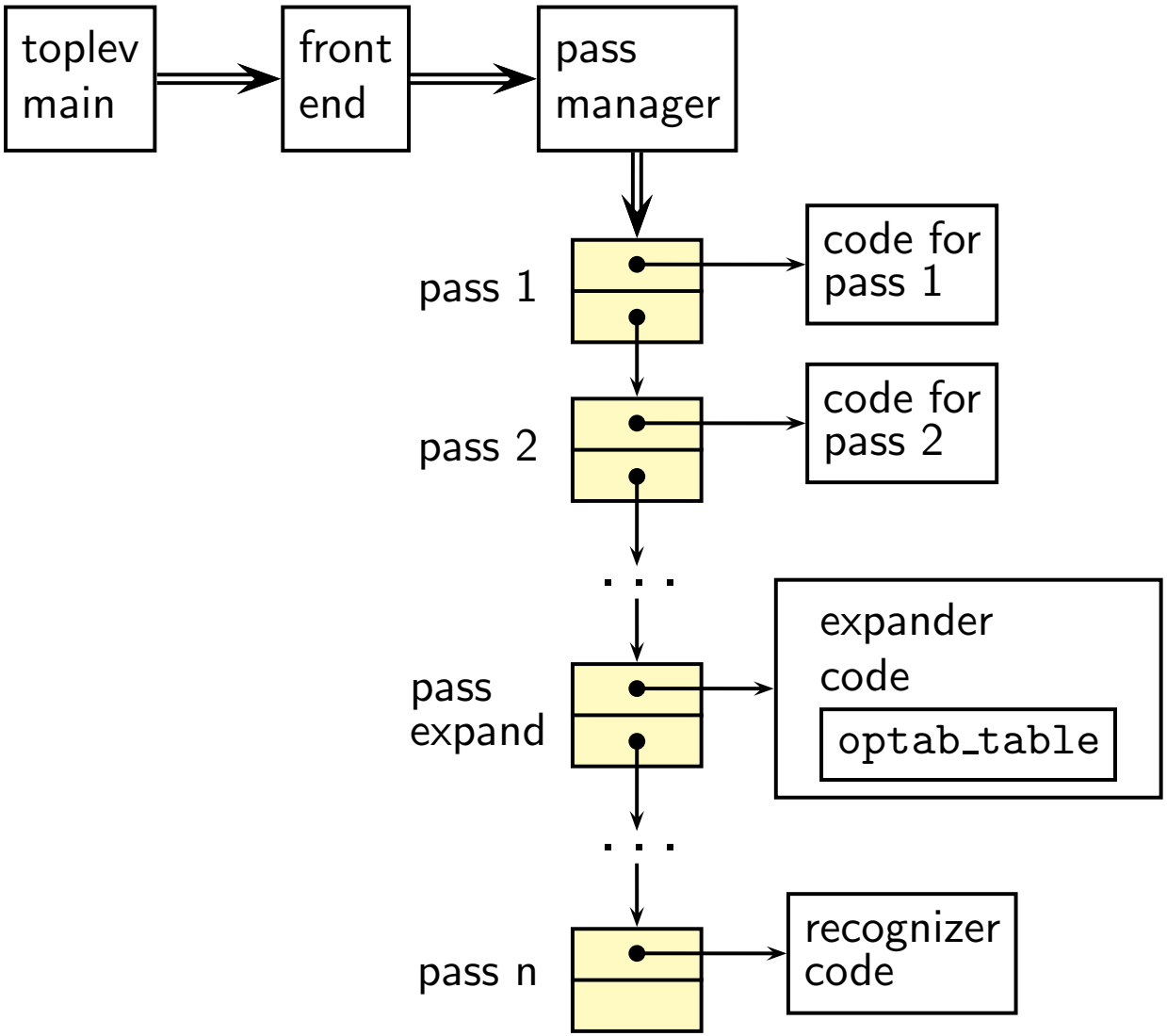
Plugin Structure in `cc1`



Double arrow represents control flow whereas single arrow represents pointer or index

For simplicity, we have included all passes in a single list. Actually passes are organized into five lists and are invoked as five different sequences

Plugin Structure in `cc1`



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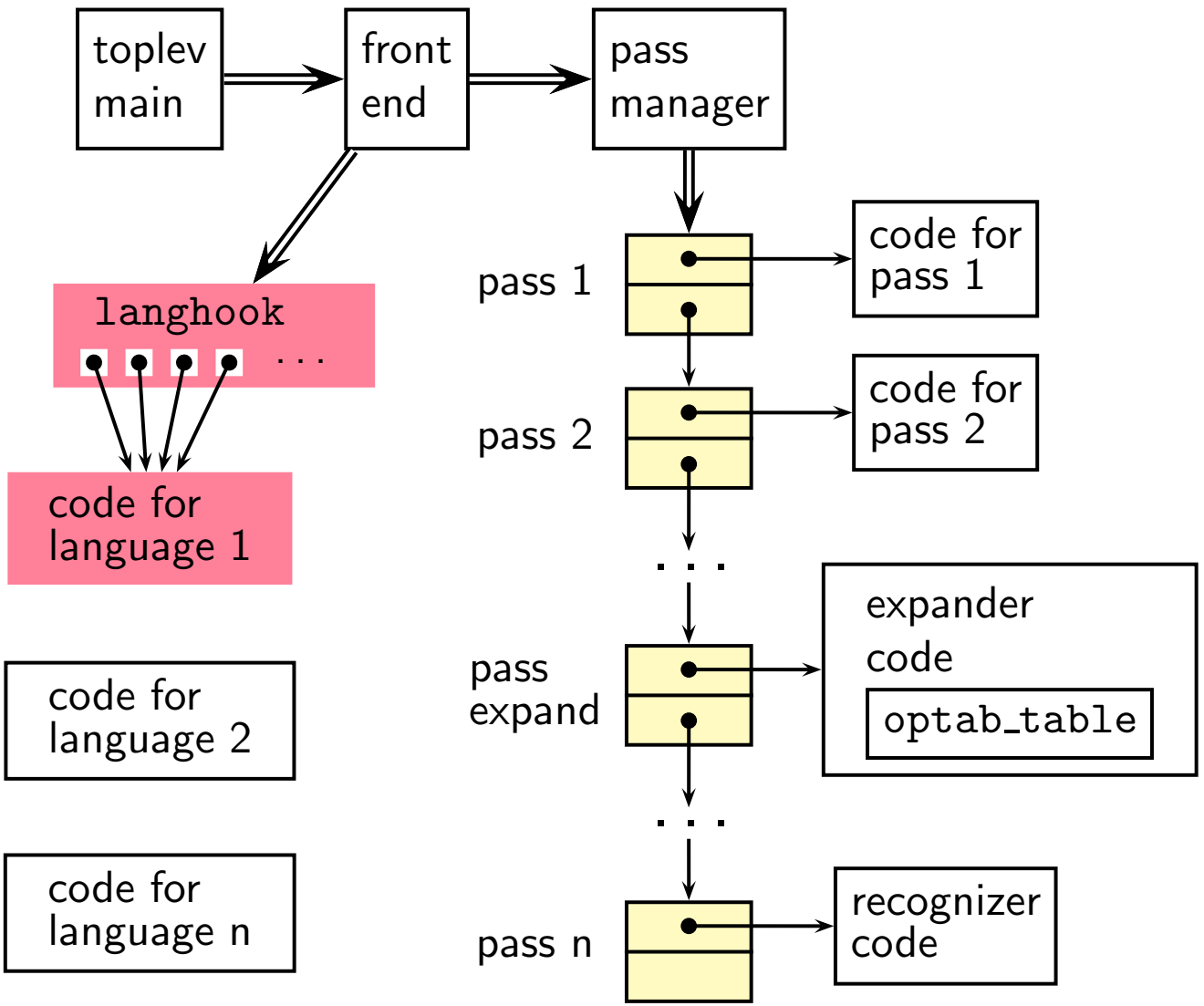

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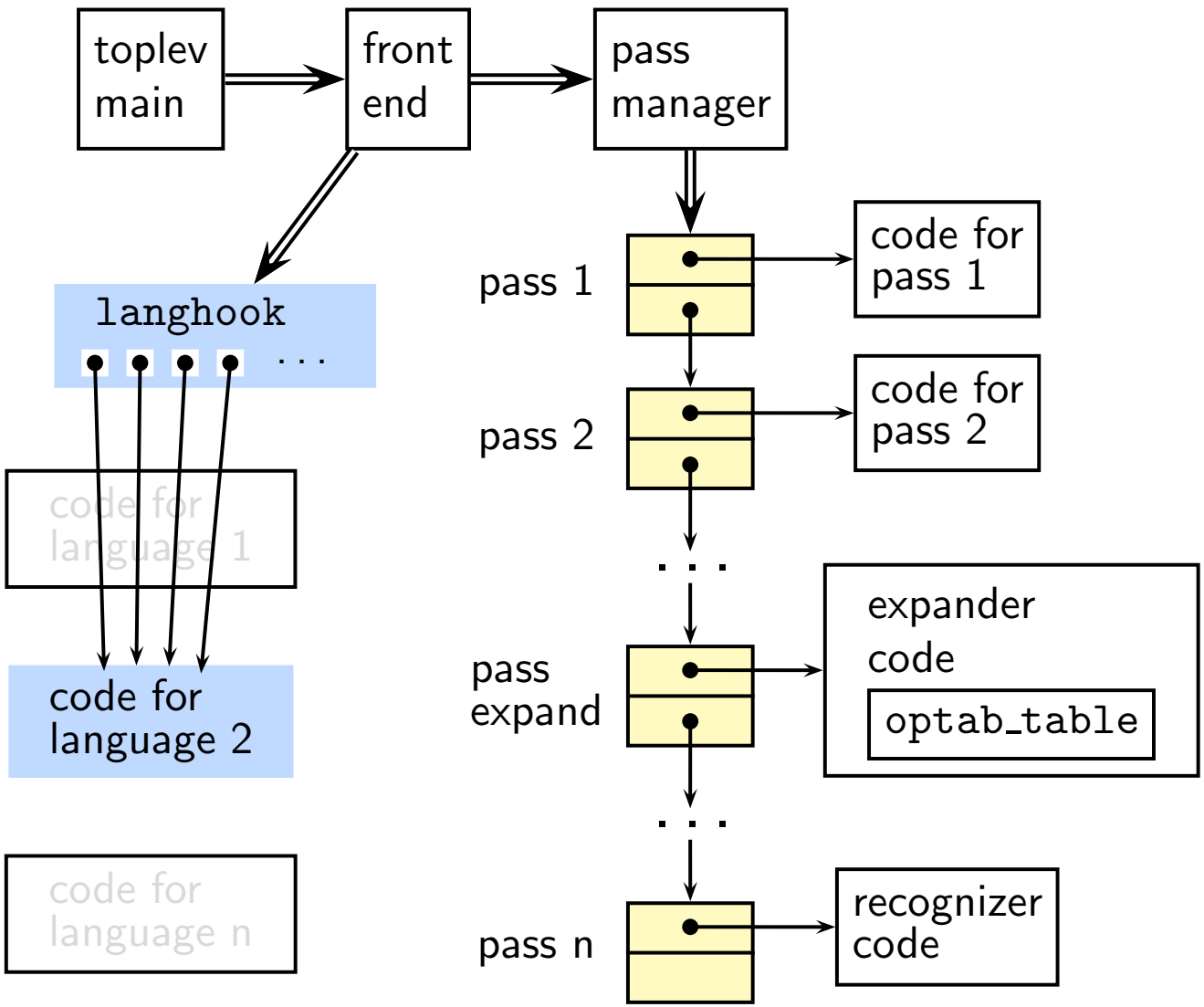
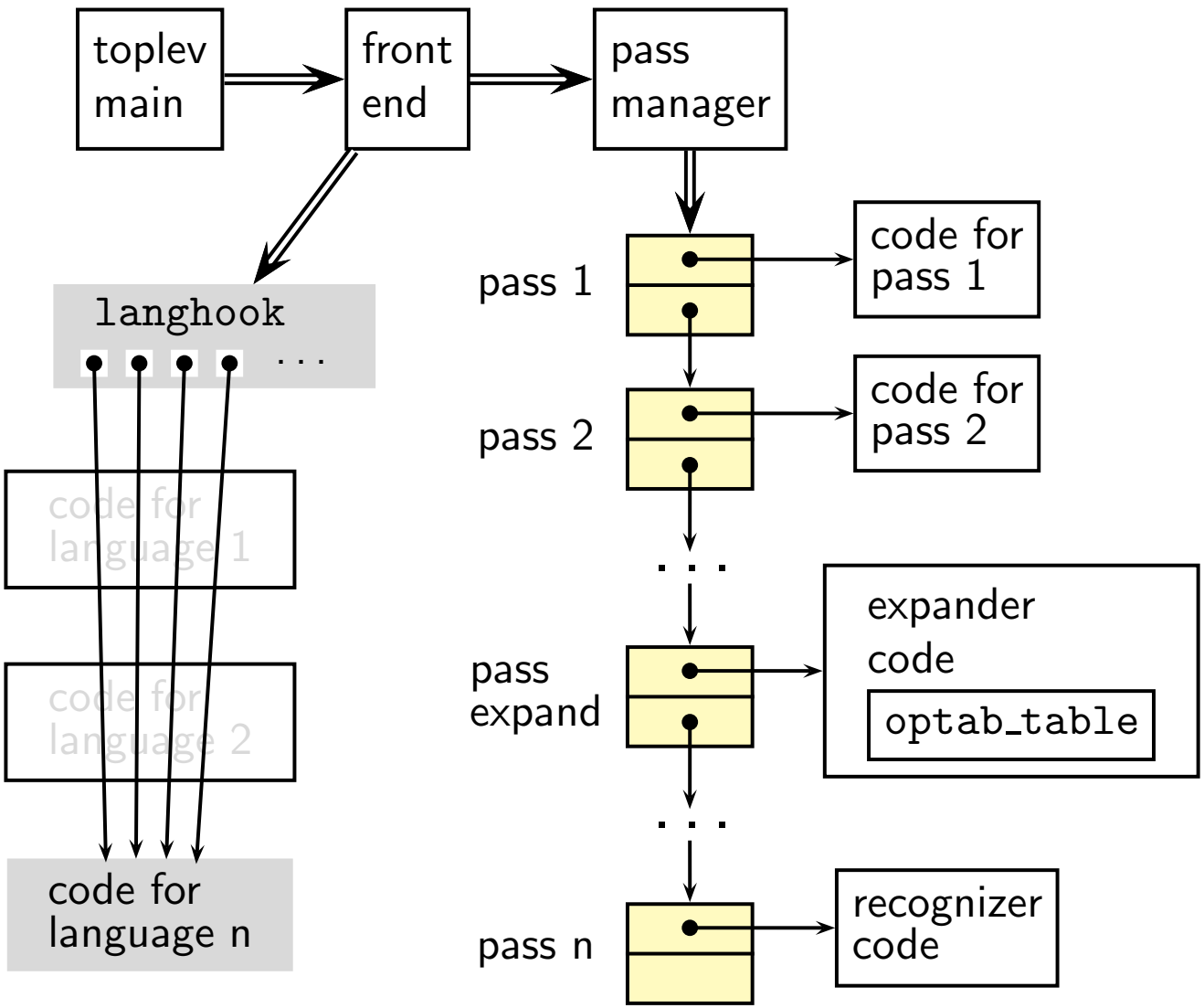


Plugin Structure in `cc1`



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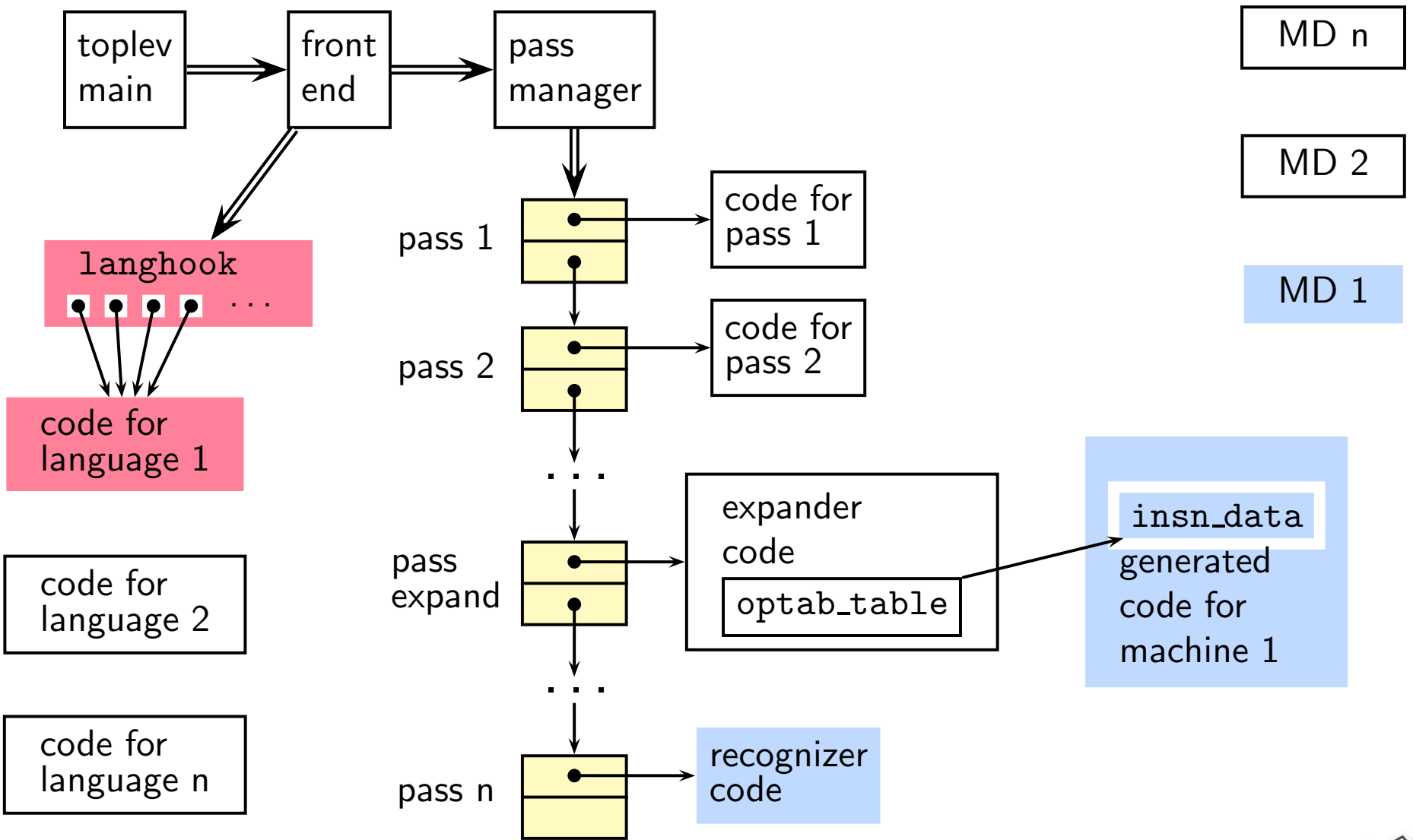

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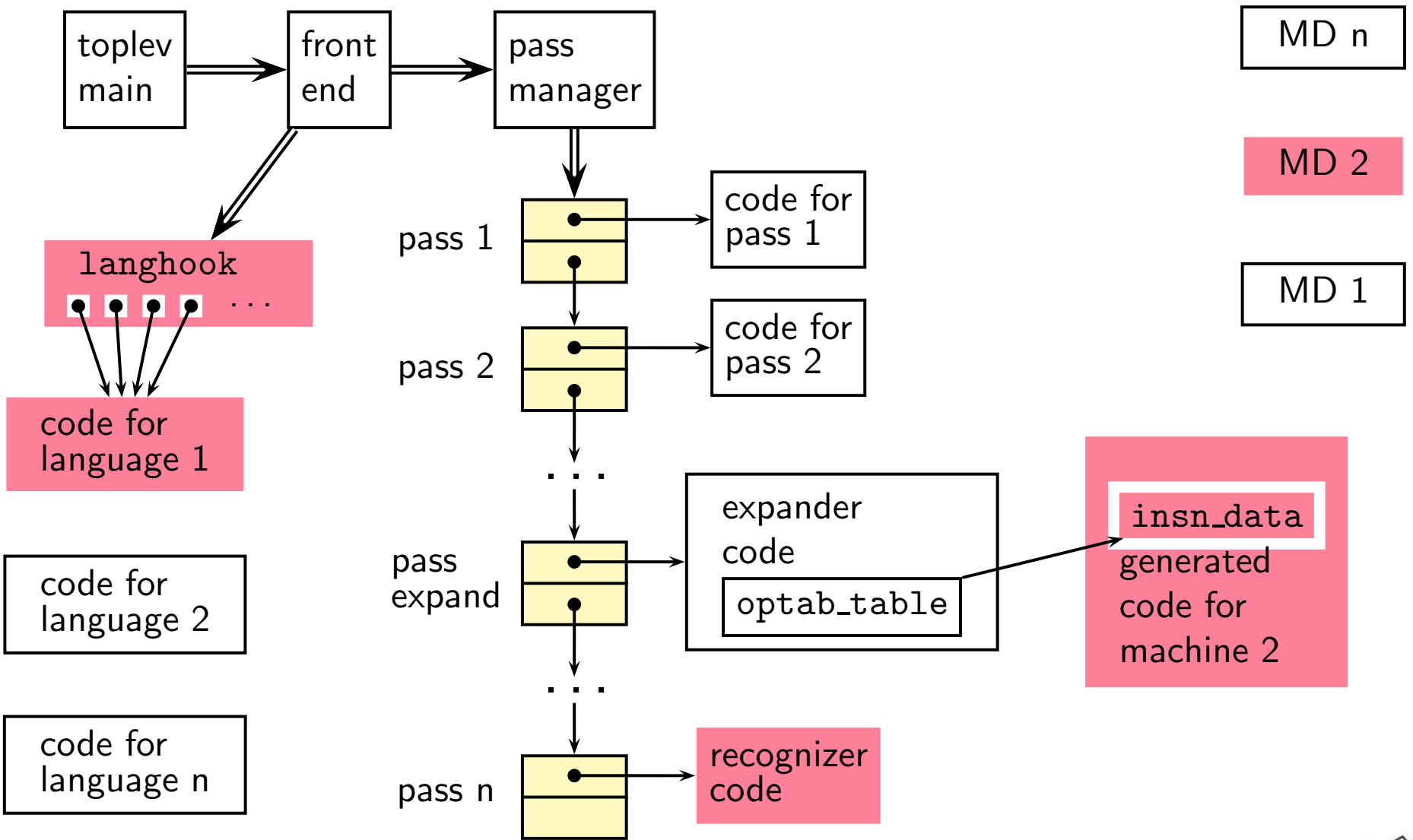
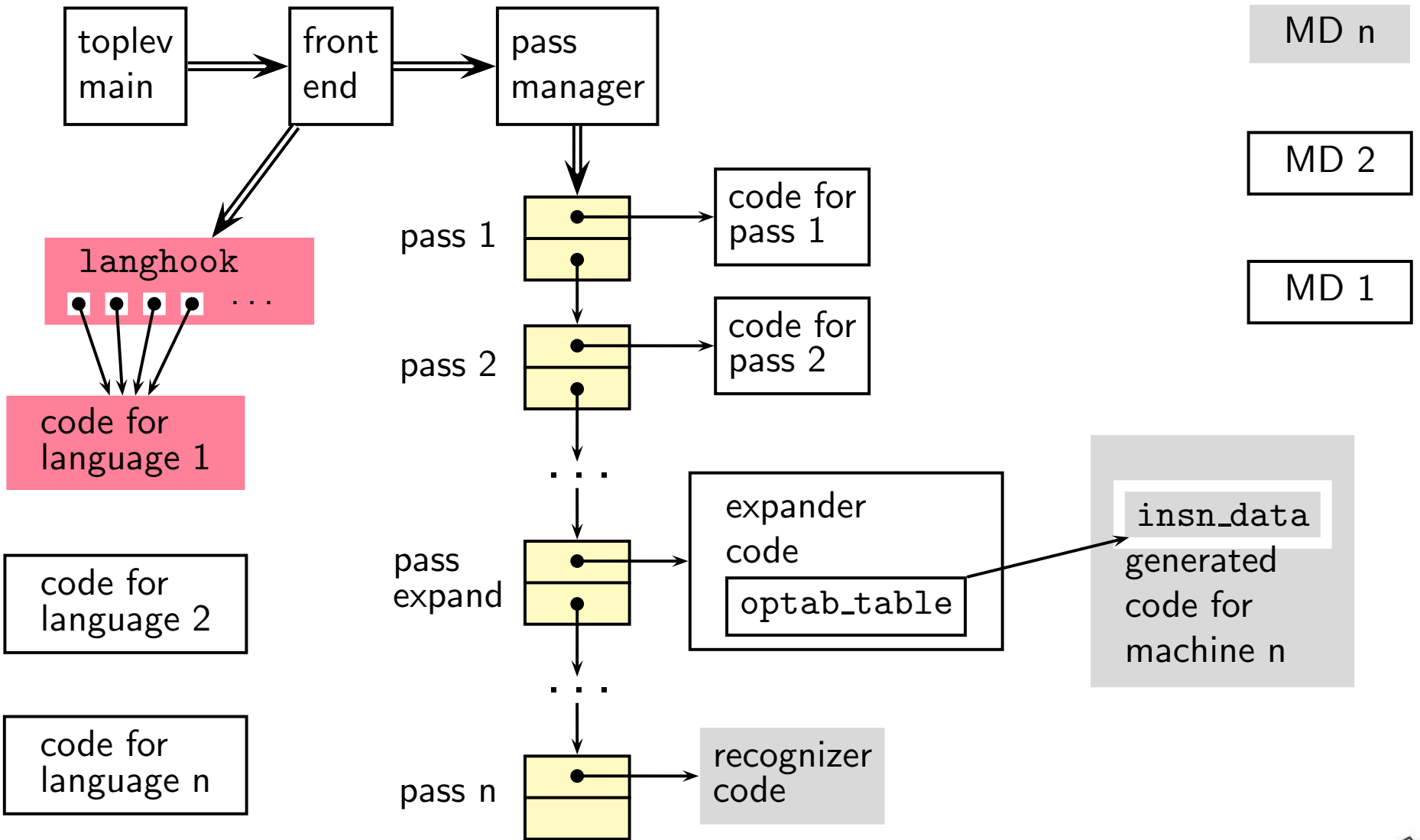


Plugin Structure in `cc1`

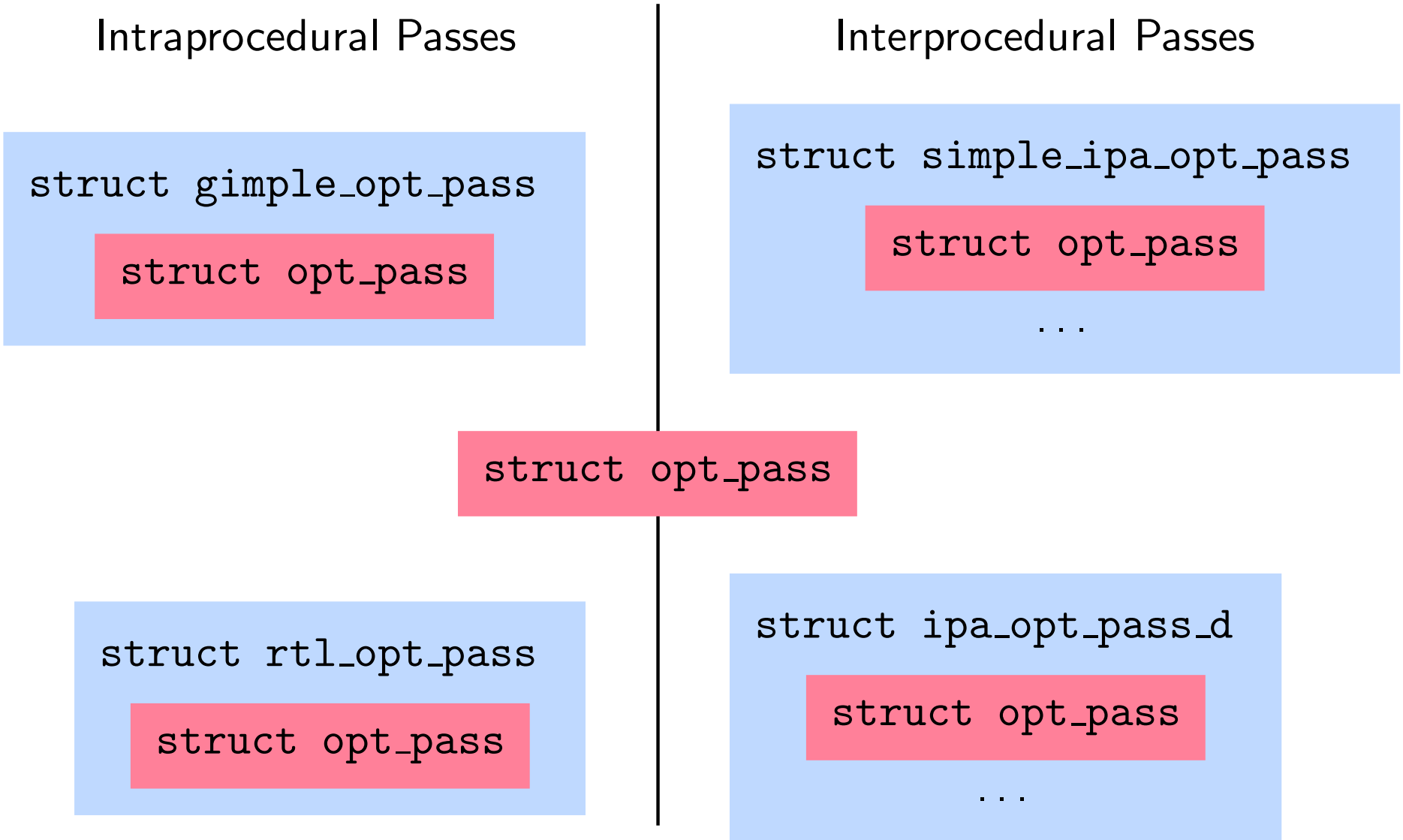


Front End Plugin

Important fields of `struct lang_hooks` instantiated for C

```
#define LANG_HOOKS_FINISH c_common_finish
#define LANG_HOOKS_PARSE_FILE c_common_parse_file
#define LANG_HOOKS_WRITE_GLOBALS c_write_global_declarations
```

Plugins for Pass Specifications



Plugins for Intraprocedural Passes

```
struct opt_pass
{
  enum opt_pass_type type;
  const char *name;
  bool (*gate) (void);
  unsigned int (*execute) (void);
  struct opt_pass *sub;
  struct opt_pass *next;
  int static_pass_number;
  timevar_id_t tv_id;
  unsigned int properties_required;
  unsigned int properties_provided;
  unsigned int properties_destroyed;
  unsigned int todo_flags_start;
  unsigned int todo_flags_finish;
};
```

```
struct gimple_opt_pass
{
  struct opt_pass pass;
};

struct rtl_opt_pass
{
  struct opt_pass pass;
};
```

Plugins for Interprocedural Passes on a Translation Unit

Pass variable: `all_simple_ipa_passes`

```
struct simple_ipa_opt_pass
{
  struct opt_pass pass;
};
```

Plugins for Interprocedural Passes across a Translation Unit

Pass variable: `all_regular_ipa_passes`

```
struct ipa_opt_pass_d
{
  struct opt_pass pass;
  void (*generate_summary) (void);
  void (*read_summary) (void);
  void (*write_summary) (struct cgraph_node_set_def *,
                         struct varpool_node_set_def *);
  void (*write_optimization_summary)(struct cgraph_node_set_def *,
                                     struct varpool_node_set_def *);
  void (*read_optimization_summary) (void);
  void (*stmt_fixup) (struct cgraph_node *, gimple *);
  unsigned int function_transform_todo_flags_start;
  unsigned int (*function_transform) (struct cgraph_node *);
  void (*variable_transform) (struct varpool_node *);
};
```

Predefined Pass Lists

Pass List	Purpose
`all_lowering_passes`	AST to CFG translation
`all_small_ipa_passes`	Interprocedural passes restricted to a single translation unit
`all_regular_ipa_passes`	Interprocedural passes on a translation unit as well as across translation units (during WPA/IPA of LTO)
`all_late_ipa_passes`	Interprocedural passes on partitions created by LTO (after WPA/IPA)
`all_lto_gen_passes`	Passes to encode program for LTO
`all_passes`	Intraprocedural passes on GIMPLE and RTL

Registering a Pass as a Static Plugin

1. Write the driver function in your file
2. Declare your pass in file `tree-pass.h`:
   `extern struct gimple_opt_pass your_pass_name;`
3. Add your pass to the appropriate pass list in `init_optimization_passes()` using the macro `NEXT_PASS`
4. Add your file details to `$SOURCE/gcc/Makefile.in`
5. Configure and build gcc
   (For simplicity, you can make `cc1` only)
6. Debug `cc1` using ddd/gdb if need arises
   (For debuging `cc1` from within `gcc`, see:
   `http://gcc.gnu.org/ml/gcc/2004-03/msg01195.html`)

Part 3

Dynamic Plugins in GCC

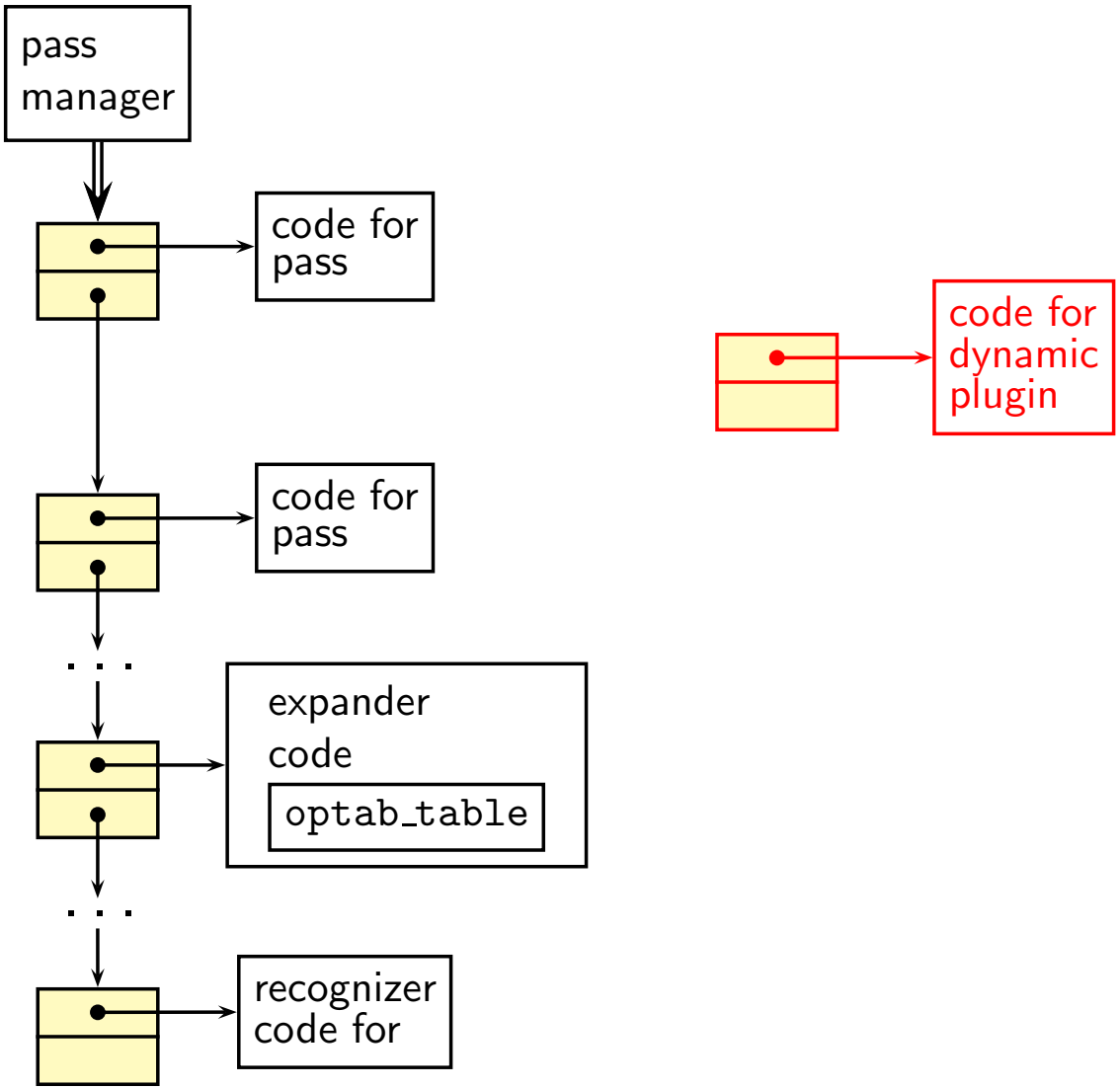
Dynamic Plugins

- Supported on platforms that support `-ldl -rdynamic`
- Loaded using `dlopen` and invoked at pre-determined locations in the compilation process
- Command line option

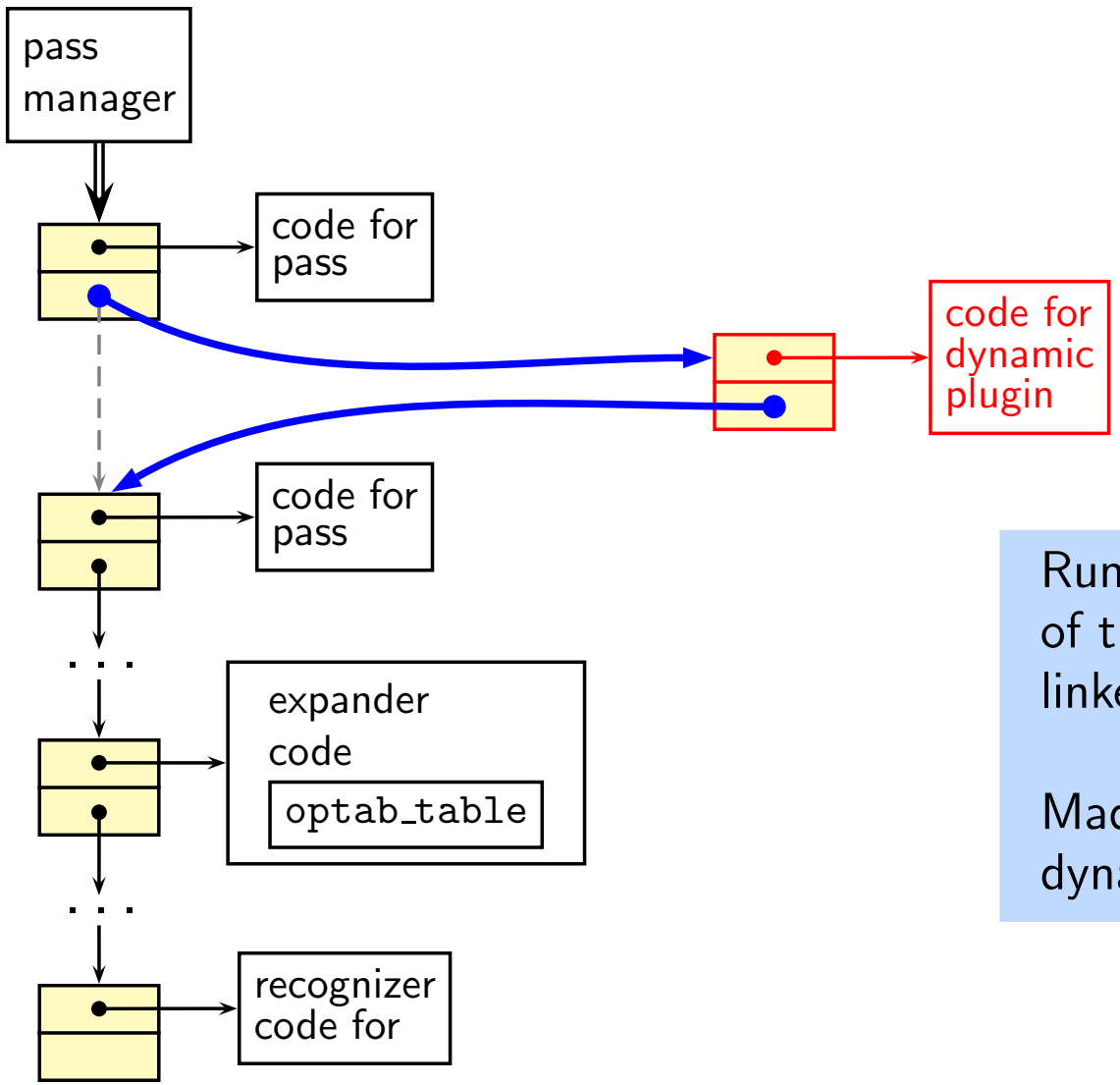
  `-fplugin=/path/to/name.so`

  Arguments required can be supplied as name-value pairs

The Mechanism of Dynamic Plugin



The Mechanism of Dynamic Plugin



Runtime initialization of the appropriate linked list of passes

Made possible by dynamic linking

Specifying an Example Pass

```
struct simple_ipa_opt_pass pass_plugin = {
  {
    SIMPLE_IPA_PASS,
    "dynamic_plug",                 /*  name */
    0,                              /*  gate */
    execute_pass_plugin,            /*  execute */
    NULL,                           /*  sub */
    NULL,                           /*  next */
    0,                              /*  static pass number */
    TV_INTEGRATION,                 /*  tv_id */
    0,                              /*  properties required */
    0,                              /*  properties provided */
    0,                              /*  properties destroyed */
    0,                              /*  todo_flags start */
    0                               /*  todo_flags end */
  }
};
```

Registering Our Pass as a Dynamic Plugin

```
struct register_pass_info pass_info = {
  &(pass_plugin.pass),      /* Address of new pass, here, the
                               struct opt_pass field of
                               simple_ipa_opt_pass defined above */
  "pta",                    /* Name of the reference pass (string
                               in the structure specification) for
                               hooking up the new pass.  */
  0,                        /* Insert the pass at the specified
                               instance number of the reference
                               pass. Do it for every instance if
                               it is 0. */
  PASS_POS_INSERT_AFTER     /* how to insert the new pass:
                               before, after, or replace. Here we
                               are inserting our pass the pass
                               named pta */
};
```

Registering Callback for Our Pass for a Dynamic Plugins

```
int plugin_init(struct plugin_name_args *plugin_info,
    struct plugin_gcc_version *version)
{ /*  Plugins are activiated using this callback  */

  register_callback (
      plugin_info->base_name,     /* char *name: Plugin name,
                                     could be any name.
                                     plugin_info->base_name
                                     gives this filename */
      PLUGIN_PASS_MANAGER_SETUP,  /* int event: The event code.
                                     Here, setting up a new
                                     pass */
      NULL,                       /* The function that handles
                                     the event */
      &pass_info);                /* plugin specific data */

  return 0;
}
```


Makefile for Creating and Using a Dynamic Plugin

```
CC = $(INSTALL_D)/bin/g++
PLUGIN_SOURCES = new-pass.c
PLUGIN_OBJECTS = $(patsubst %.c,%.o,$(PLUGIN_SOURCES ))
GCCPLUGINS_DIR = $(shell $(CC) -print-file-name=plugin)
CFLAGS+= -fPIC -O2
INCLUDE = -Iplugin/include

%.o : %.c
$(CC) $(CFLAGS) $(INCLUDE) -c $<

new-pass.so: $(PLUGIN_OBJECTS)
        $(CC) $(CFLAGS) $(INCLUDE) -shared $^ -o $@

test_plugin: test.c
        $(CC) -fplugin=./new-pass.so $^ -o $@ -fdump-tree-all
```

Part 4

Flow of Control in the Generated Compiler

Walking the Maze of a Large Code Base

- If you use conventional editors such as `vi` or `emacs`
  - Use cscope

    ```
    cd $SOURCE
    cscope -R
    ```

  - Use ctags

    ```
    cd $SOURCE
    ctags -R
    ```

    Make sure you use `exeburant-ctags`
- Or use IDE such as `eclipse`

gcc Driver Control Flow

```
main   /* In file gcc.c */
  validate_all_switches
  lookup_compiler
  do_spec
    do_spec_2
      do_spec_1  /* Get the name of the compiler */
    execute
      pex_init
      pex_run
        pex_run_in_environment
          obj->funcs->exec_child
```

gcc Driver Control Flow

```
main   /* In file gcc.c */
   validate_all_switches
   lookup_compiler
   do_spec
      do_spec_2
         do_spec_1  /*
      execute
         pex_init
         pex_run
            pex_run_in
               obj->fu
```

Observations

- All compilers are invoked by this driver
- Assembler is also invoked by this driver
- Linker is invoked in the end by default

cc1 Top Level Control Flow

```
main                    /* In file main.c */
|   toplev_main    /* In file toplev.c */
|   |   decode_options
|   |   do_compile
|   |   |   compile_file
|   |   |       lang_hooks.parse_file => c_common_parse_file
|   |   |       lang_hooks.decls.final_write_globals =>
|   |   |                                   c_write_global_declarations
|   |   |     targetm.asm_out.file_end
|   |   finalize
|   |
|
```


cc1 Top Level Control Flow

```
main                    /* In file main.c */
  toplev_main           /* In file toplev.c */
    decode_options
    do_compile
      compile_file
        lang_hooks                                  le
        lang_hooks
                                                    eclarations
          targetm.asm
    finalize
```

Observations

- The entire compilation is driven by functions specified in language hooks
- Not a good design!

cc1 Control Flow: Parsing for C

```
lang_hooks.parse_file => c_common_parse_file
   c_parse_file
      c_parser_translation_unit
         c_parser_external_declaration
            c_parser_declaration_or_fndef
               c_parser_declspecs /* parse declarations */
               c_parser_compound_statement
               finish_function    /* finish parsing */
                  c_genericize
                  cgraph_finalize_function
                  /* finalize AST of a function */
```

cc1 Control Flow: Parsing for C

```
lang_hooks.parse_file => c_common_parse_file
  c_parse_file
    c_parser_translation_unit
      c_parser_external_declaration
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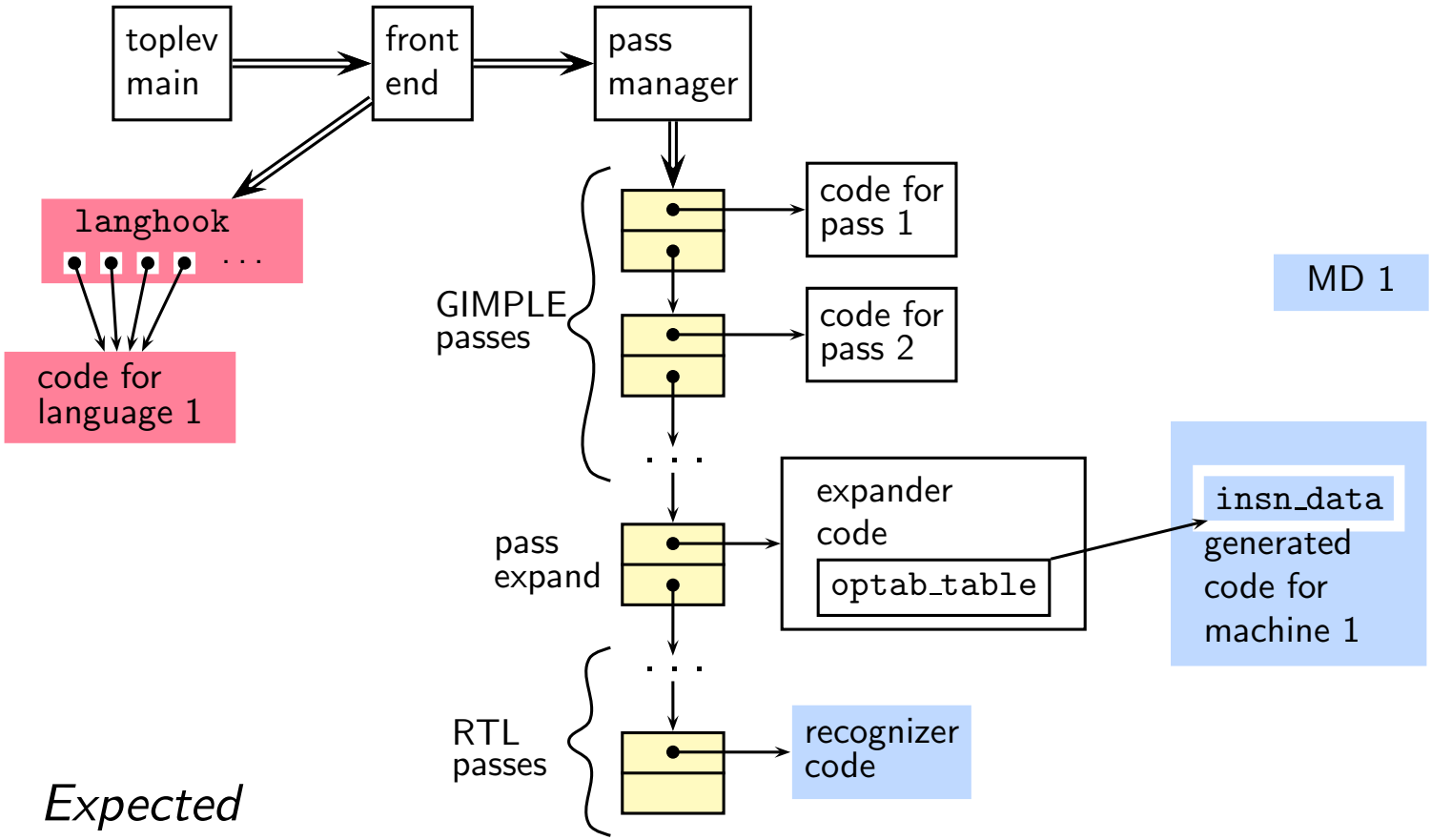
cc1 Control Flow: Parsing for C

```
lang_hooks.parse_file => c_common_parse_file
   c_parse_file
      c_parser_translation_unit
         c_parser_external_declaration
            c_parser_declaration_or_fndef
               c_pars                                    ns */
               c_pars
               finish                                    /
                  c_g
                  cgr
                  /*
```

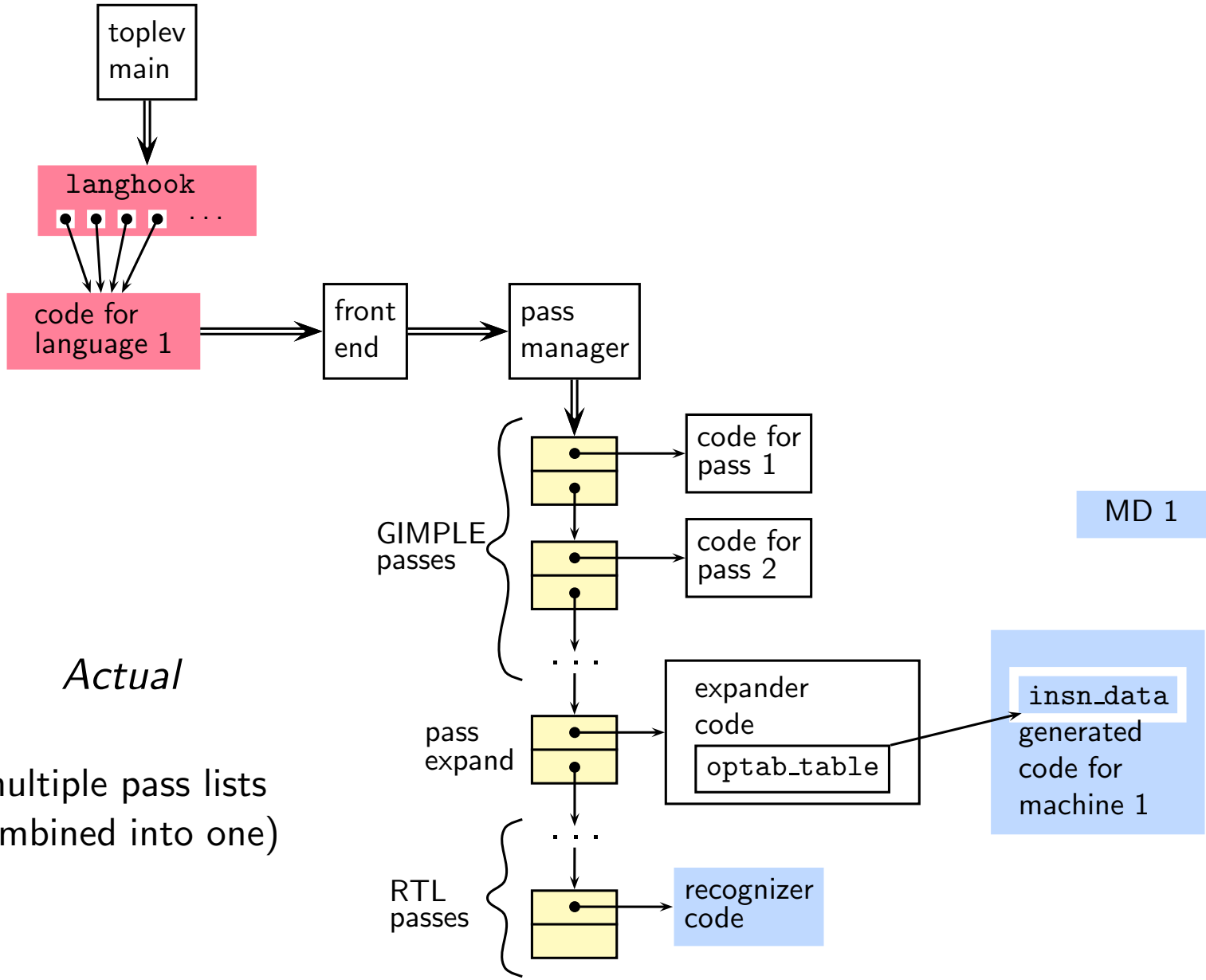
Observations

- GCC has moved to a recursive descent parser from version 4.1.0
- Earlier parser was generated using Bison specification

Expected Vs. Actual Schematic of the Front End



Expected Vs. Actual Schematic of the Front End



cc1 Control Flow: Lowering Passes for C

```
lang_hooks.decls.final_write_globals =>
                                    c_write_global_declarations
    cgraph_finalize_compilation_unit
       cgraph_analyze_functions      /* Create GIMPLE */
          cgraph_analyze_function
             gimplify_function_tree
                gimplify_body
                   gimplify_stmt
                      gimplify_expr
             cgraph_lower_function    /* Intraprocedural */
                tree_lowering_passes
                   execute_pass_list (all_lowering_passes)
```

cc1 Control Flow: Lowering Passes for C

```
lang_hooks.decls.final_write_globals =>
                                        c_write_global_declarations
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cc1 Control Flow: Lowering Passes for C

```
lang_hooks.decls.final_write_globals =>
                                    c_write_global_declarations
    cgraph_finalize_compilation_unit
       cgraph_analyze_functions     /* Create GIMPLE */
          cgraph_analyze_function
             gimplify
                gimpl
                   gi

             cgraph_l                                  ural */
                tree_
                   ex                                  asses)
```

Observations

- Lowering passes are language independent
- Yet they are being called from a function in language hooks
- Not a good design!

Organization of Passes

Order	Task	IR	Level	Pass data structure
1	Lowering	GIMPLE	Intra	`gimple_opt_pass`
2	Optimizations	GIMPLE	Inter	`simple_ipa_opt_pass`
3	Optimizations	GIMPLE	Inter	`ipa_opt_pass_d`
4	Optimizations	GIMPLE	Intra	`gimple_opt_pass`
5	RTL Generation	GIMPLE	Intra	`rtl_opt_pass`
6	Optimization	RTL	Intra	`rtl_opt_pass`

cc1 Control Flow: Optimization and Code Generation Passes

```
cgraph_analyze_function          /* Create GIMPLE */
...                              /* previous slide */
cgraph_optimize
   ipa_passes
      execute_ipa_pass_list(all_small_ipa_passes)  /*!in_lto_p*/
      execute_ipa_summary_passes(all_regular_ipa_passes)
      execute_ipa_summary_passes(all_lto_gen_passes)
      ipa_write_summaries
   execute_ipa_pass_list(all_late_ipa_passes)
   cgraph_expand_all_functions
       cgraph_expand_function
       /* Intraprocedural passes on GIMPLE,  */
       /* expansion pass, and passes on RTL. */
            tree_rest_of_compilation
               execute_pass_list (all_passes)
```

cc1 Control Flow: Optimization and Code Generation Passes

```
cgraph_analyze_function          /* Create GIMPLE */
...                              /* previous slide */
cgraph_optimize
  ipa_passes
    execute_ipa_pass_list(all_small_ipa_passes)  /*!in_lto_p*/
    execute_ipa_summary_passes(all_regular_ipa_passes)
    execute_ipa_summary_passes(all_lto_gen_passes)
    ipa_write_summaries
  execute_ipa_pass_list(all_late_ipa_passes)
  cgraph_expand_all_functions
    cgraph_expand_function
    /* Intraprocedural passes on GIMPLE,  */
    /* expansion pass, and passes on RTL. */
        tree_rest_of_compilation
            execute_pass_list (all_passes)
```

cc1 Control Flow: Optimization and Code Generation Passes

```
cgraph_analyze_function          /* Create GIMPLE */
...                              /* previous slide */
cgraph_optimize
   ipa_passes
      execute_ipa_pas                                  !in_lto_p*/
      execute_ipa_sum                                  ses)
      execute_ipa_sum
      ipa_write_summa
   execute_ipa_pass_l
   cgraph_expand_all_
       cgraph_expand_
       /* Intraproced
       /* expansion p
            tree_rest
               execut
```

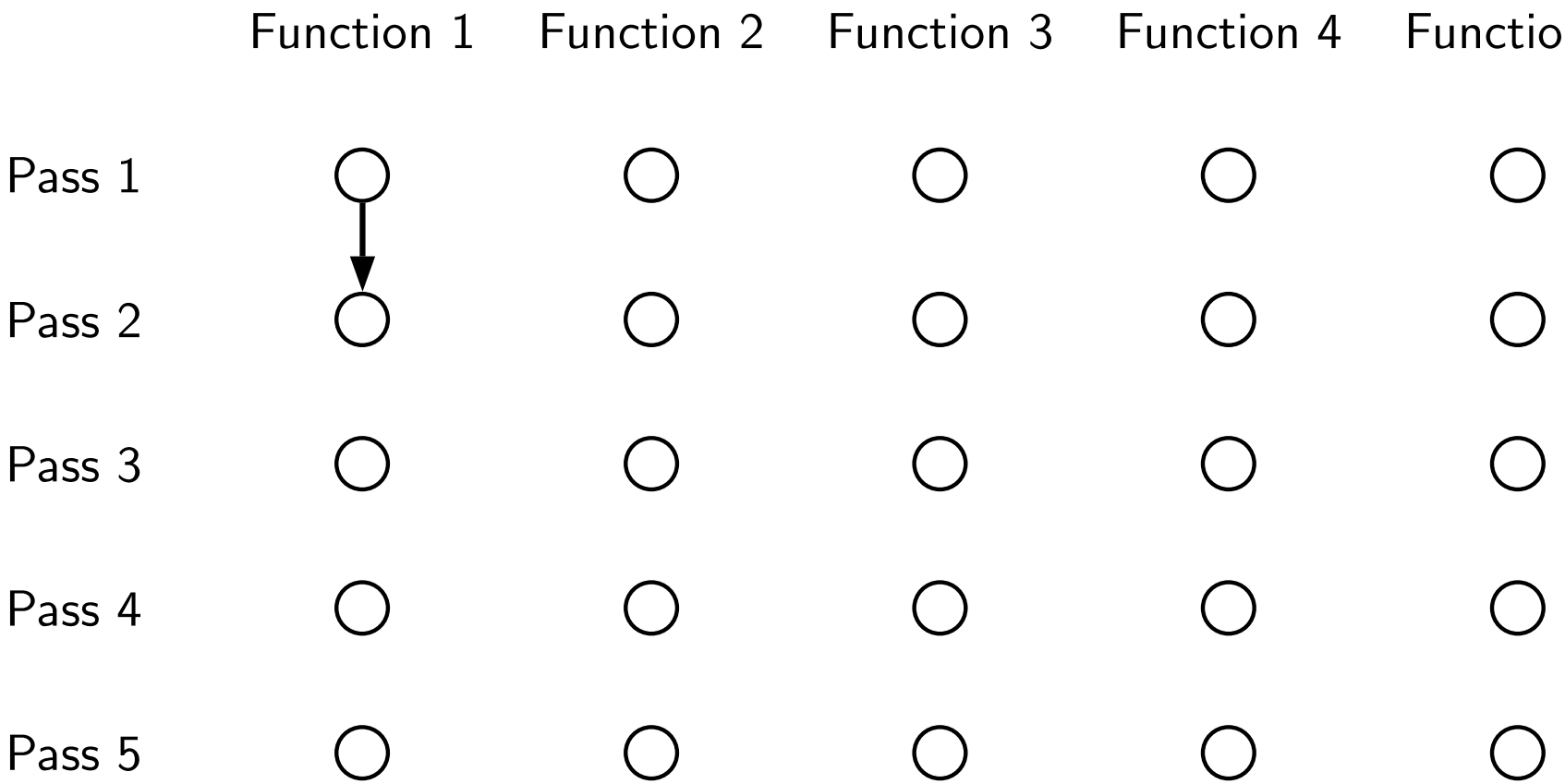
Observations

- Optimization and code generation passes are language independent
- Yet they are being called from a function in language hooks
- Not a good design!

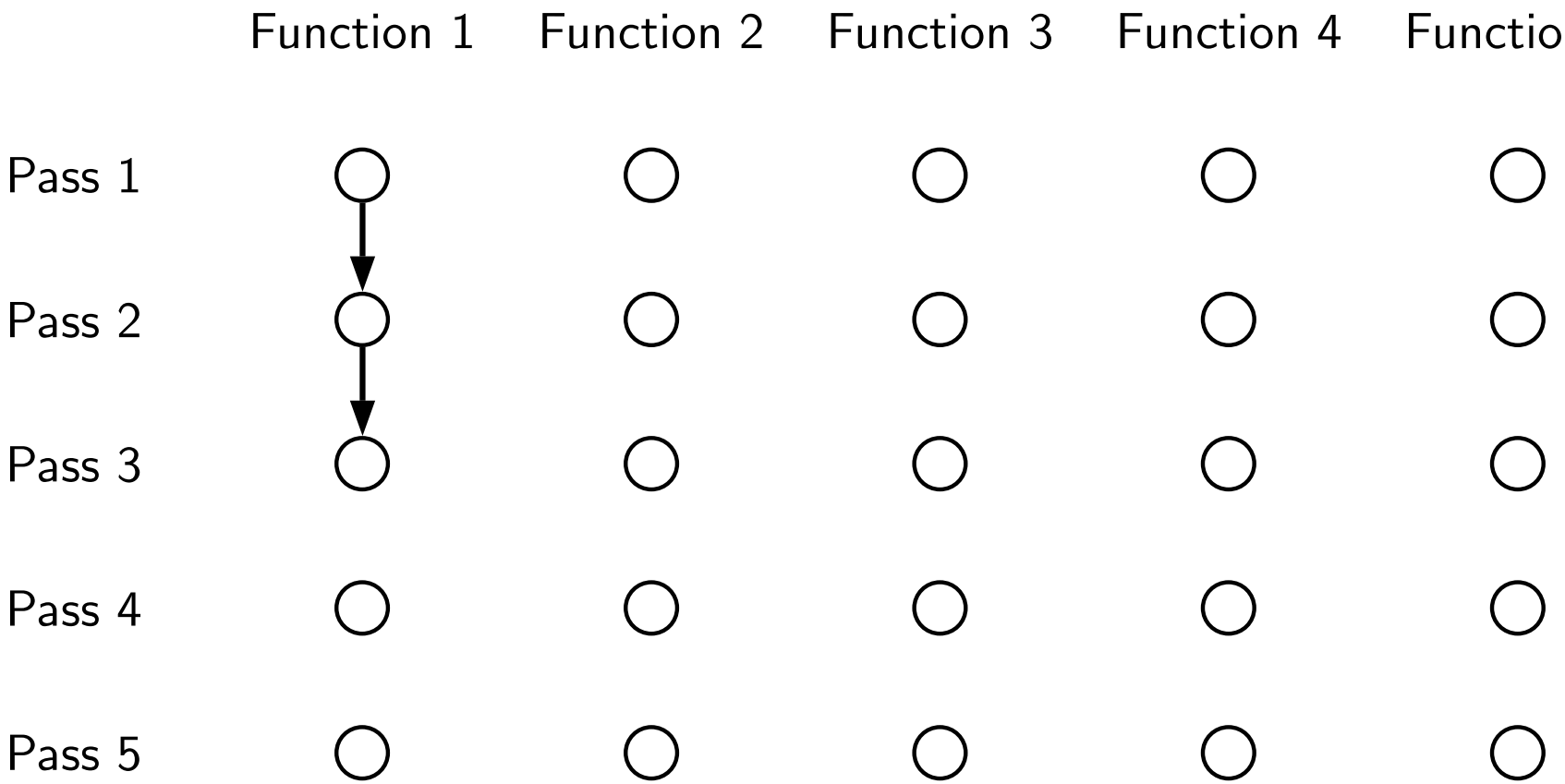
Execution Order in Intraprocedural Passes

	Function 1	Function 2	Function 3	Function 4	Function 5
Pass 1	○	○	○	○	○
Pass 2	○	○	○	○	○
Pass 3	○	○	○	○	○
Pass 4	○	○	○	○	○
Pass 5	○	○	○	○	○

Execution Order in Intraprocedural Passes



Execution Order in Intraprocedural Passes



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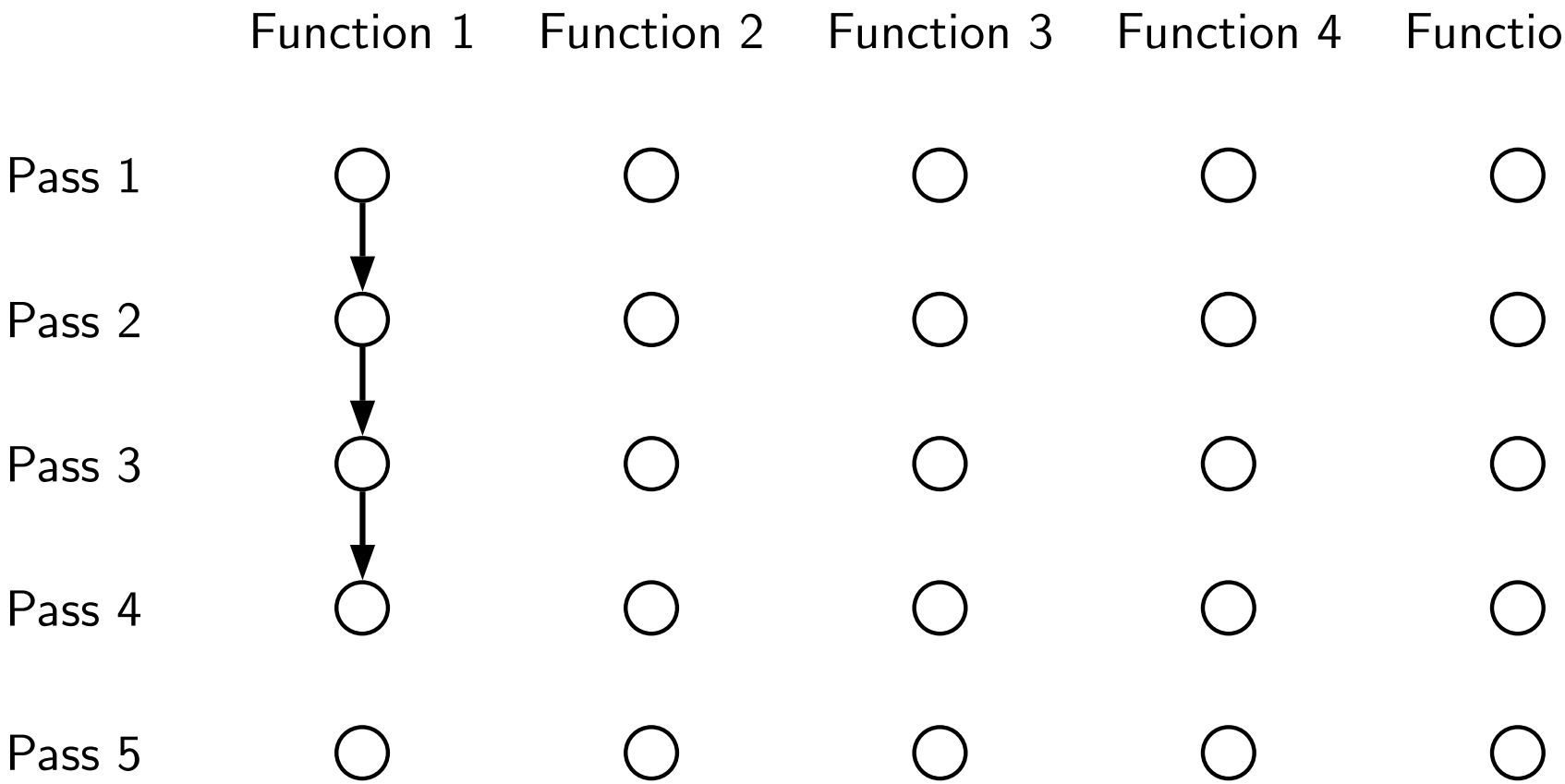
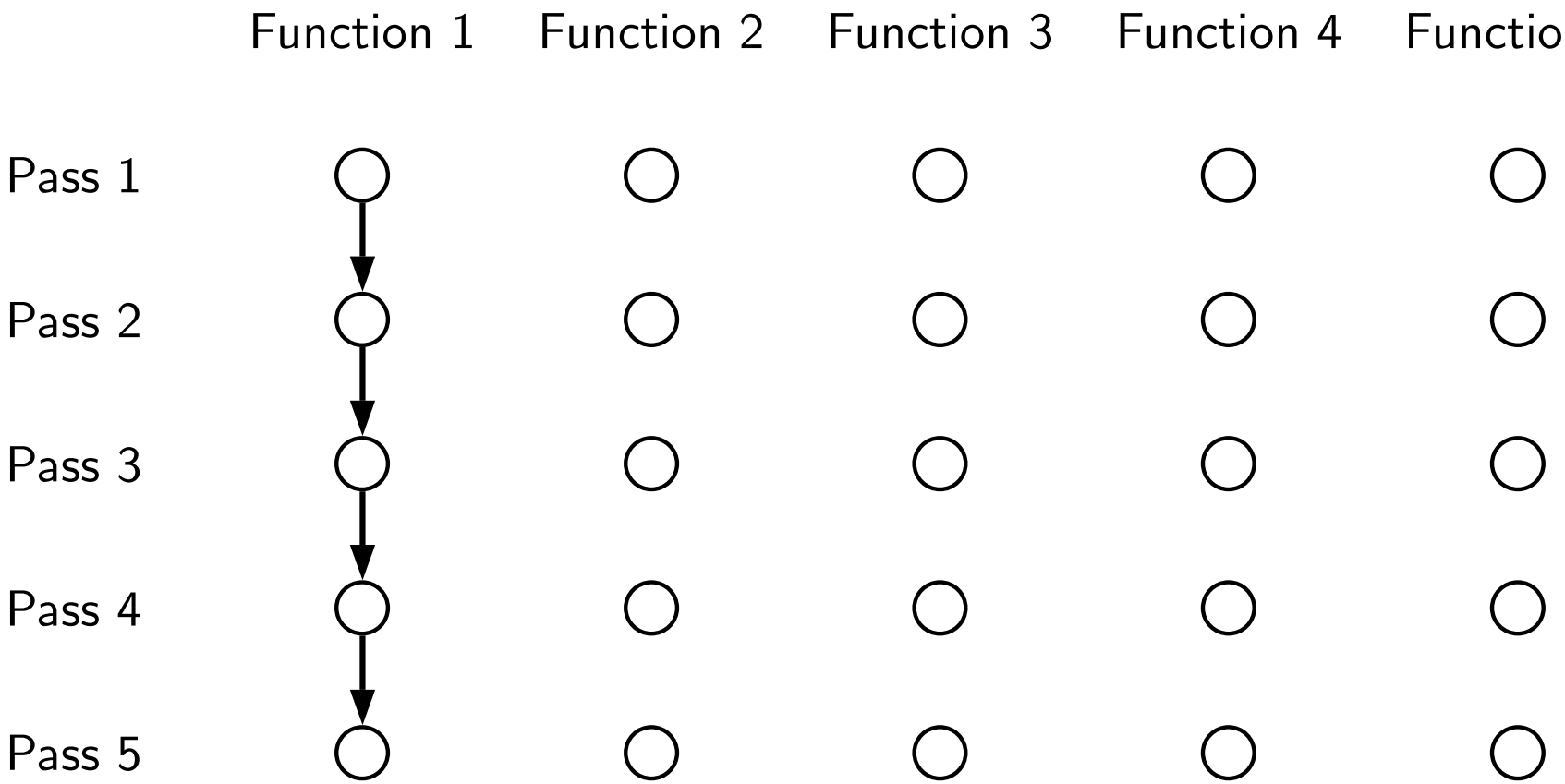


Execution Order in Intraprocedural Passes



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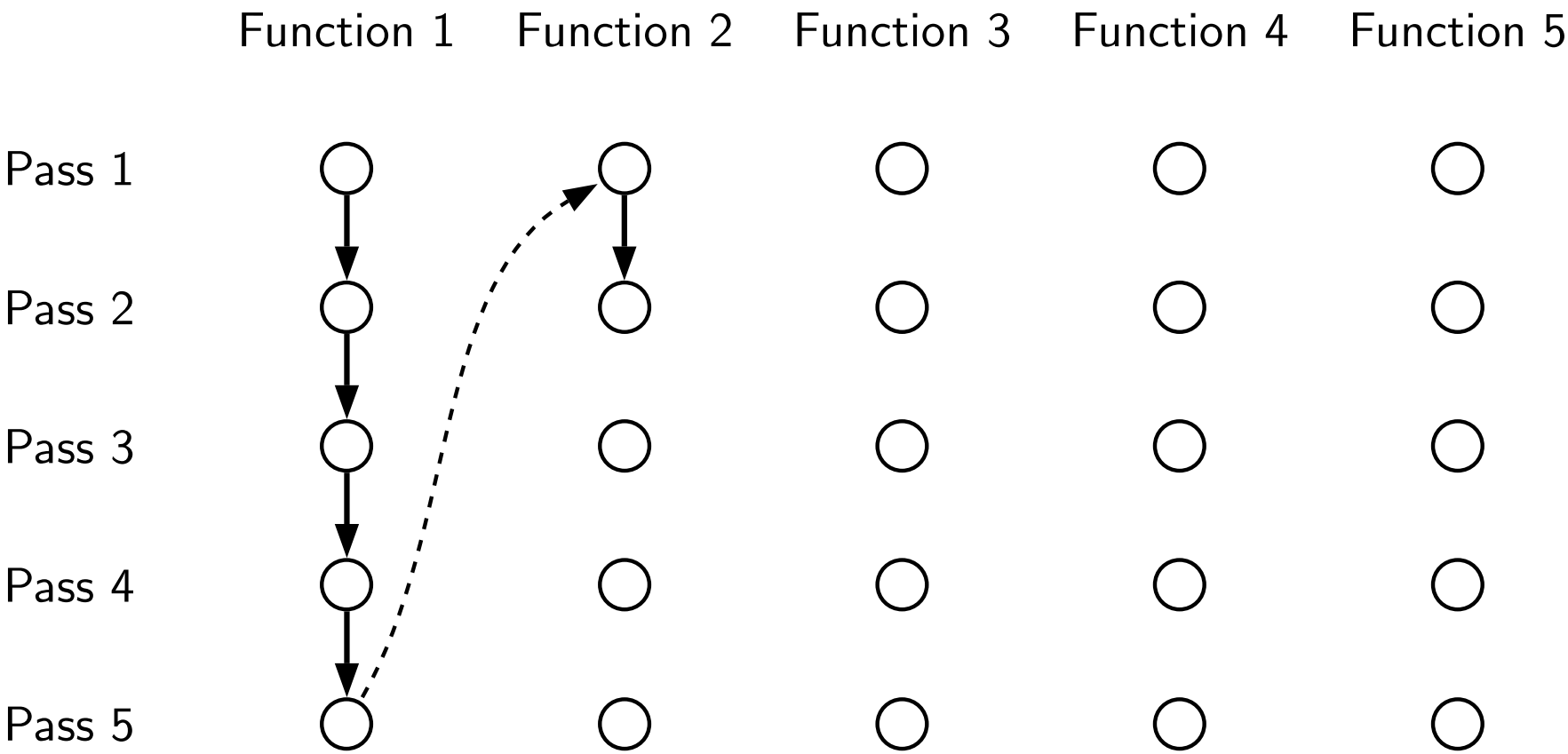

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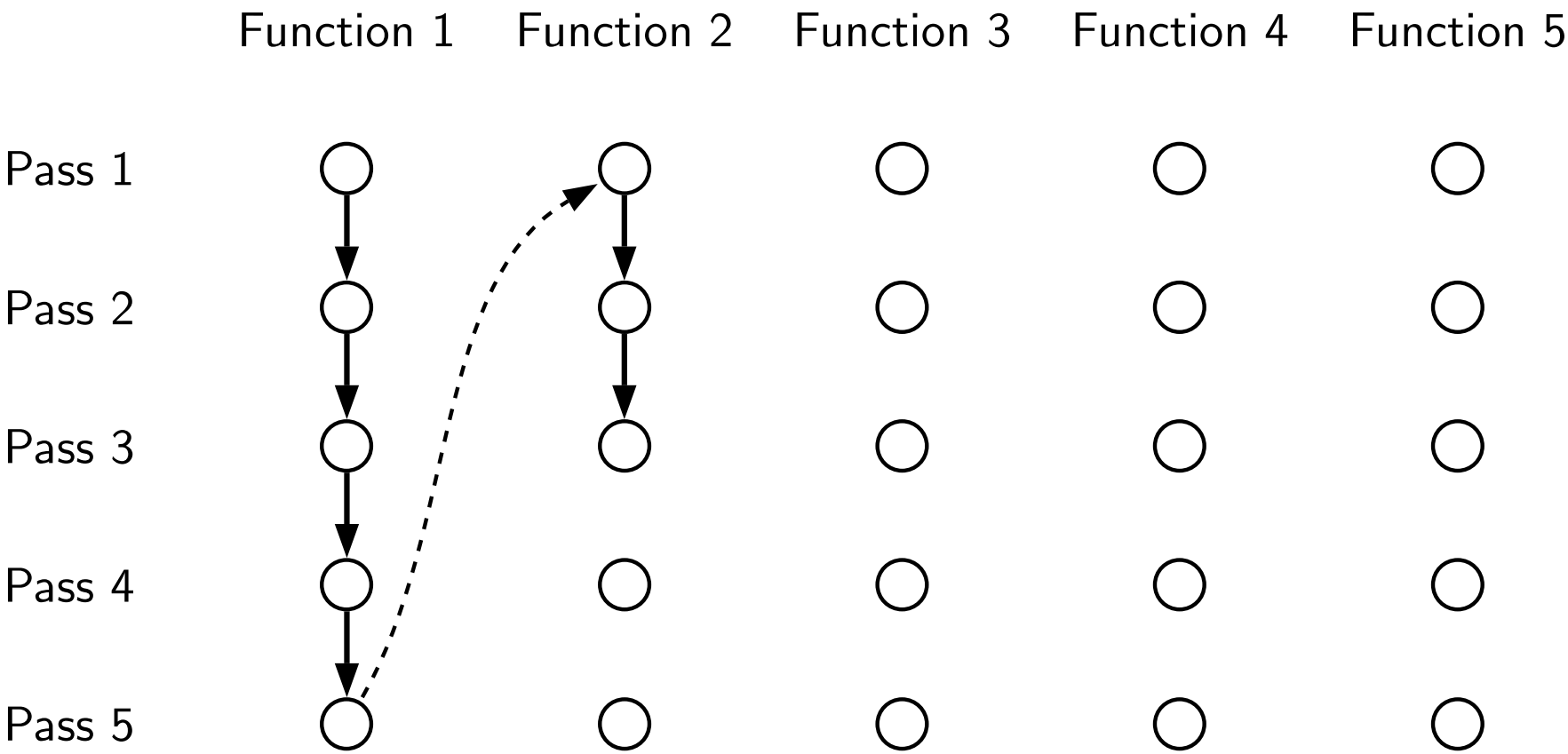
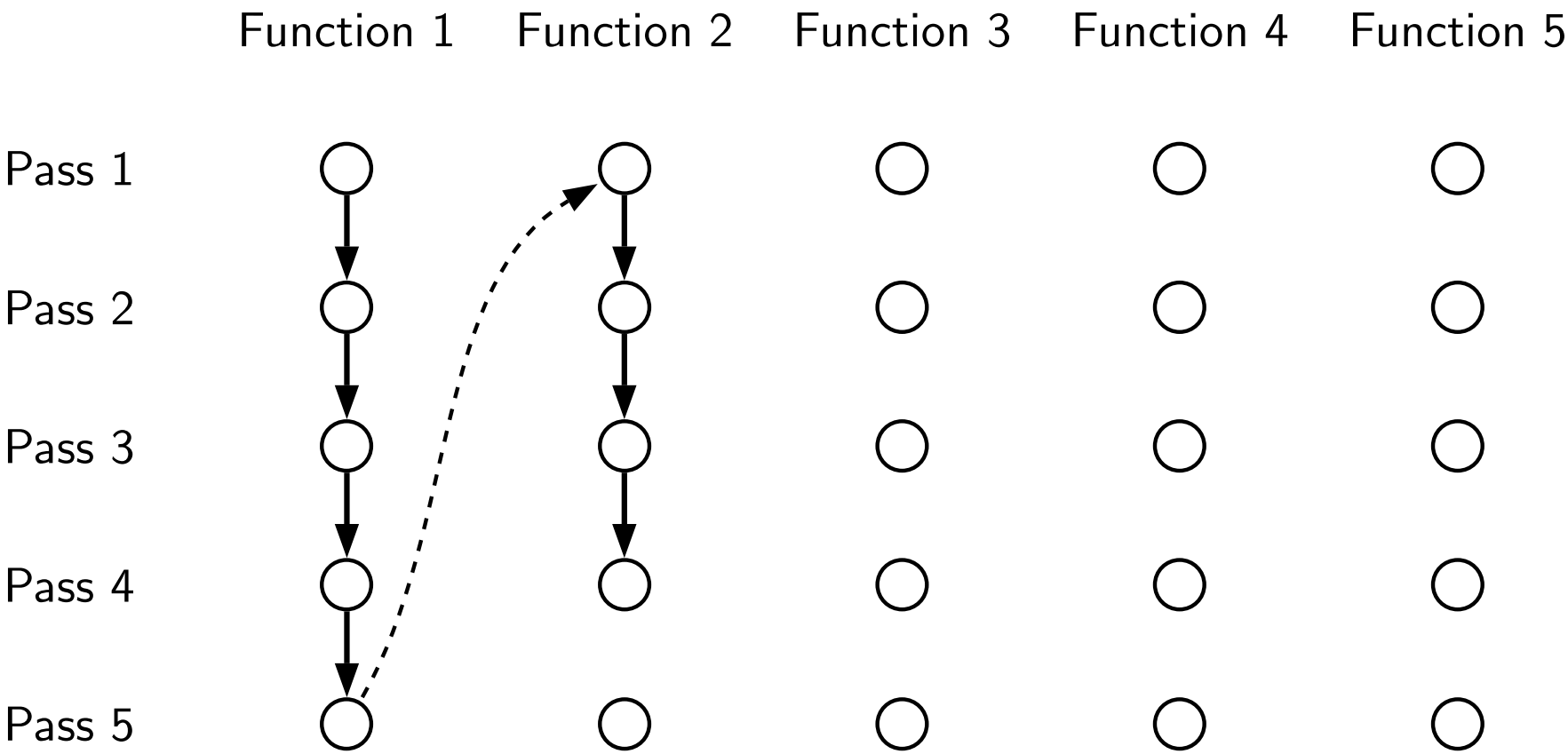
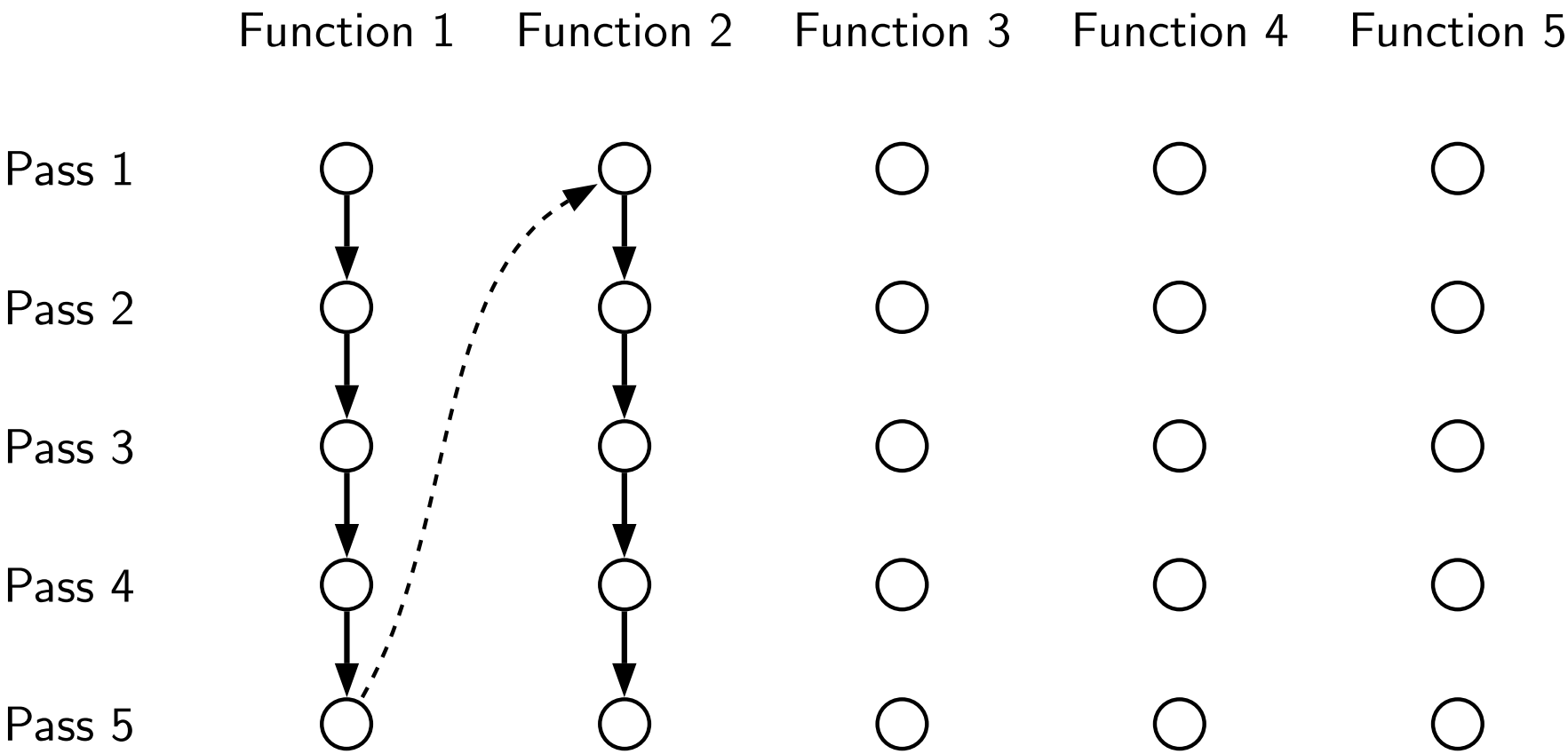


Execution Order in Intraprocedural Passes



Execution Order in Intraprocedural Passes



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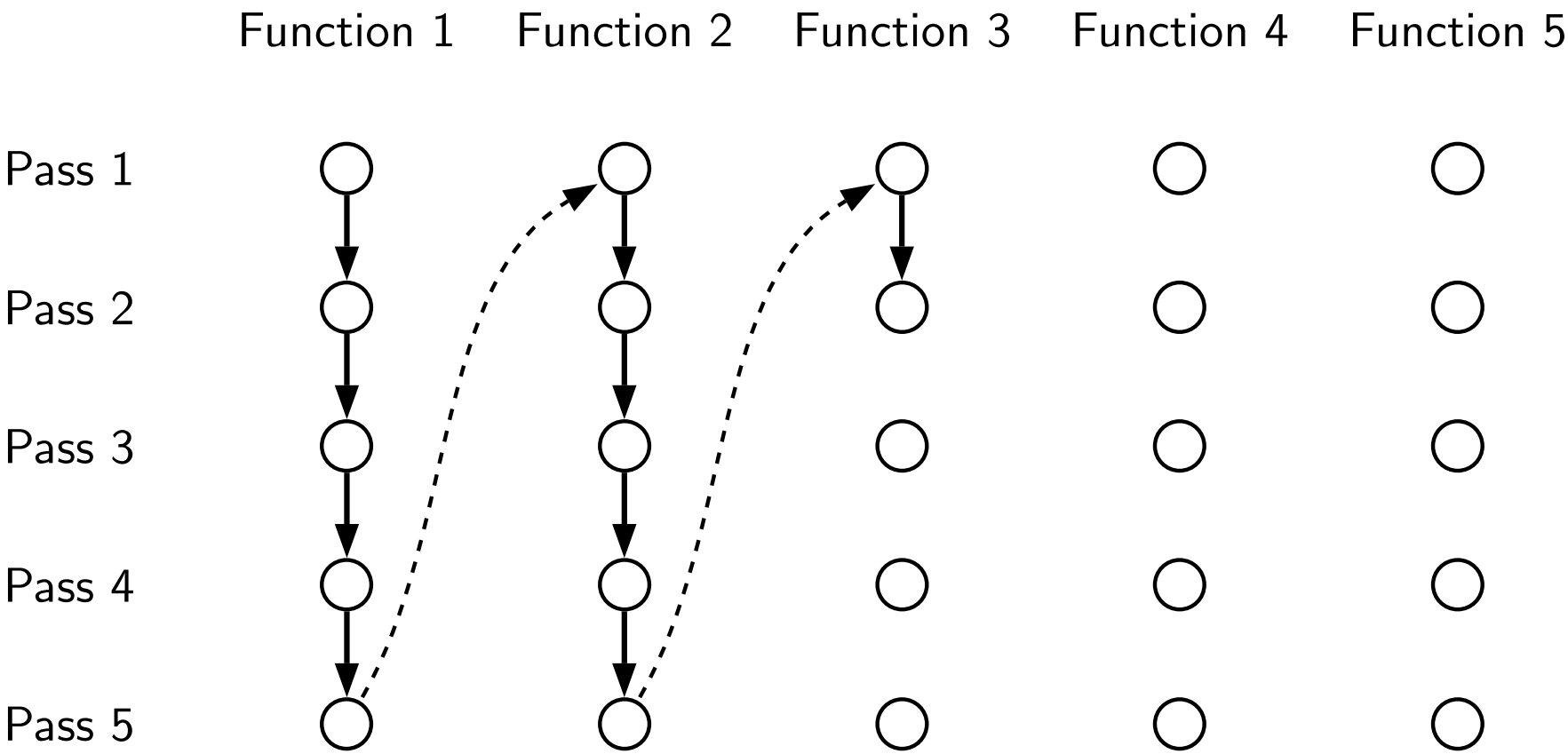

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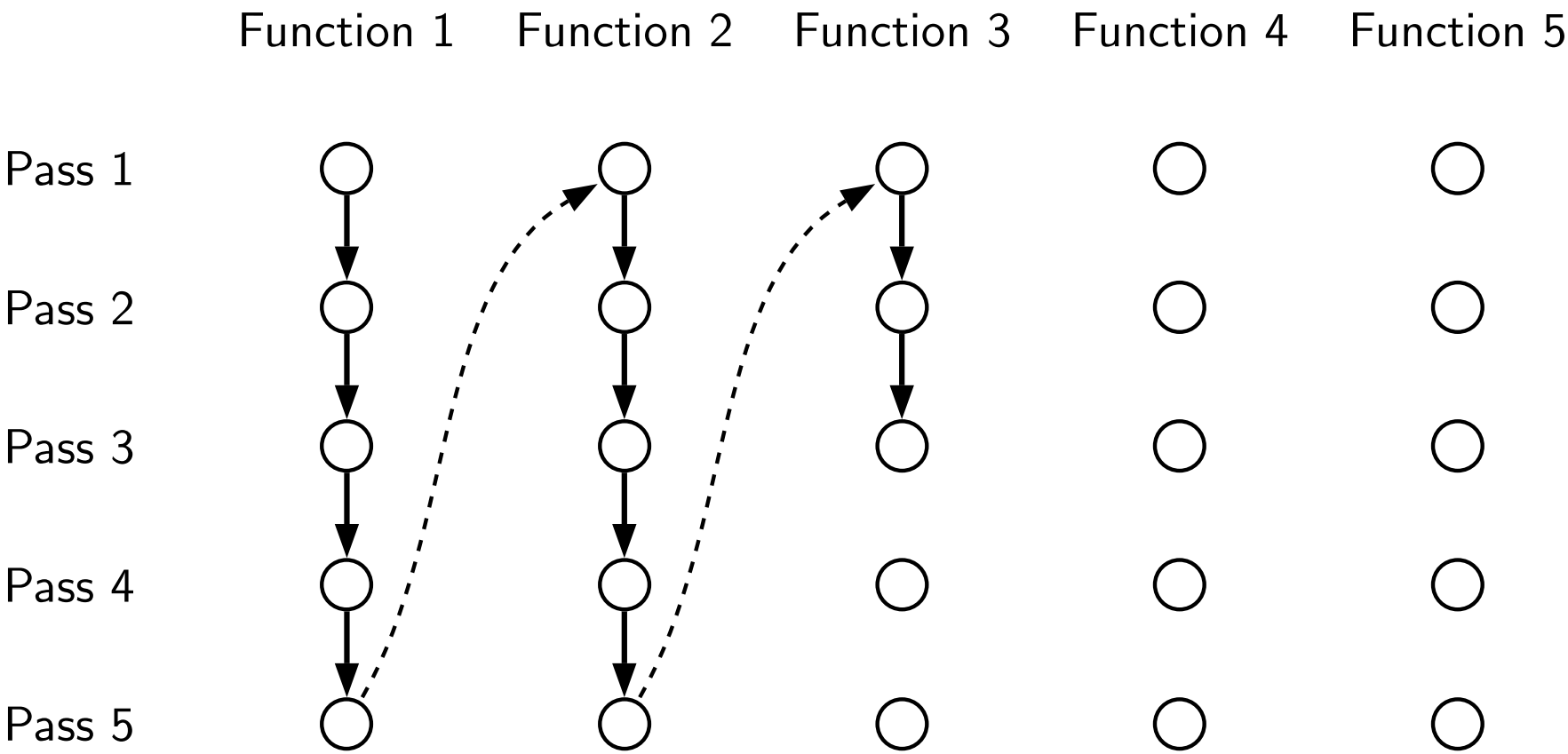

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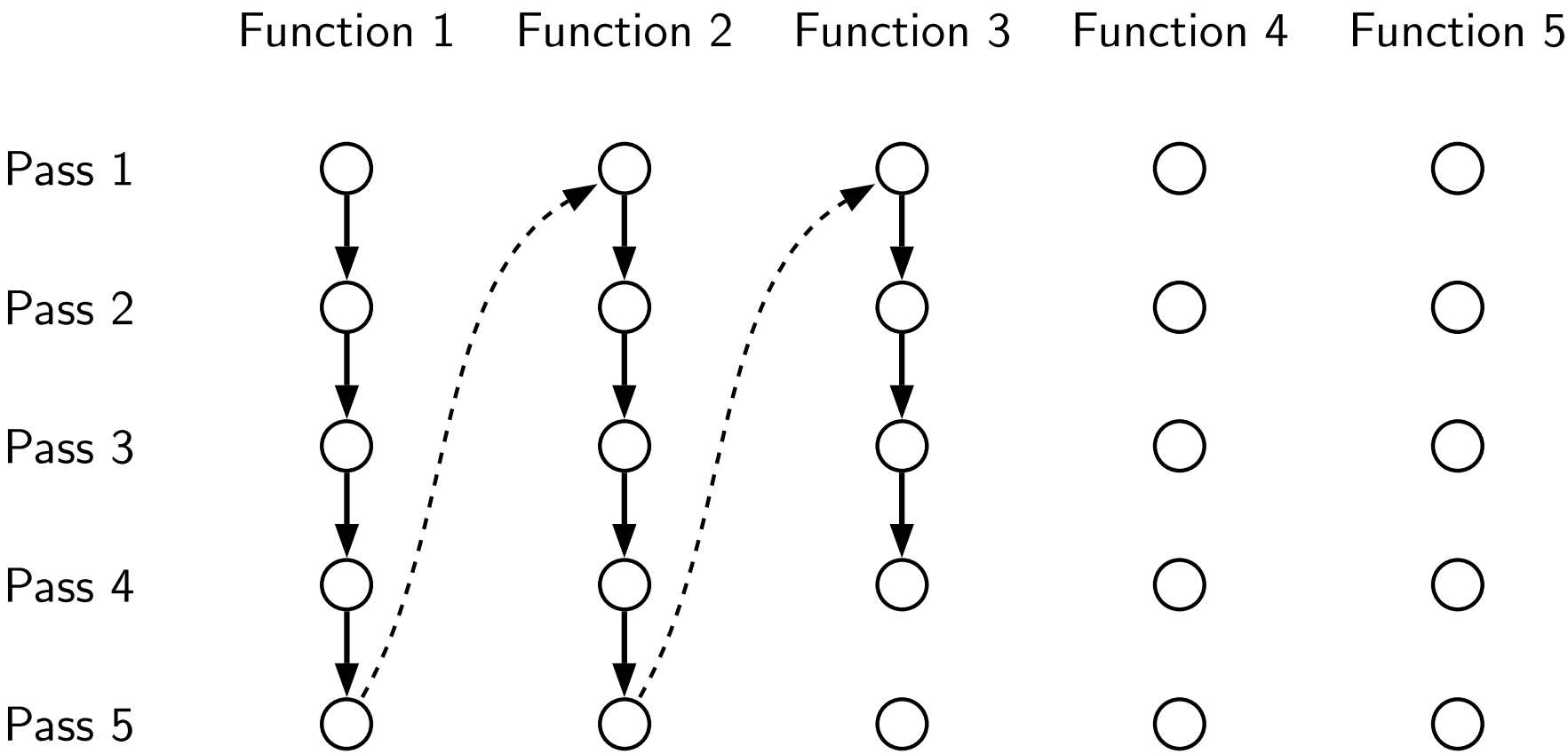

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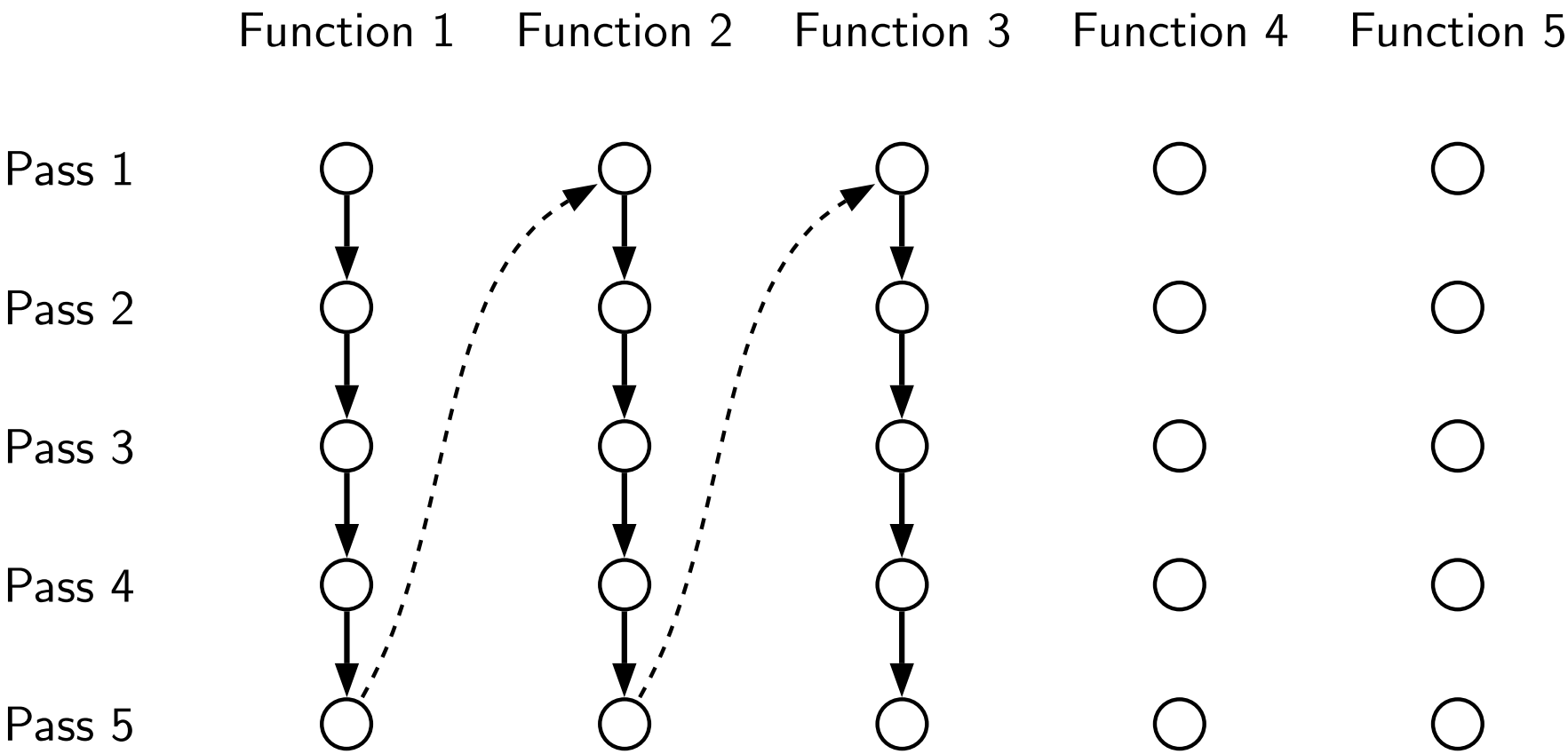

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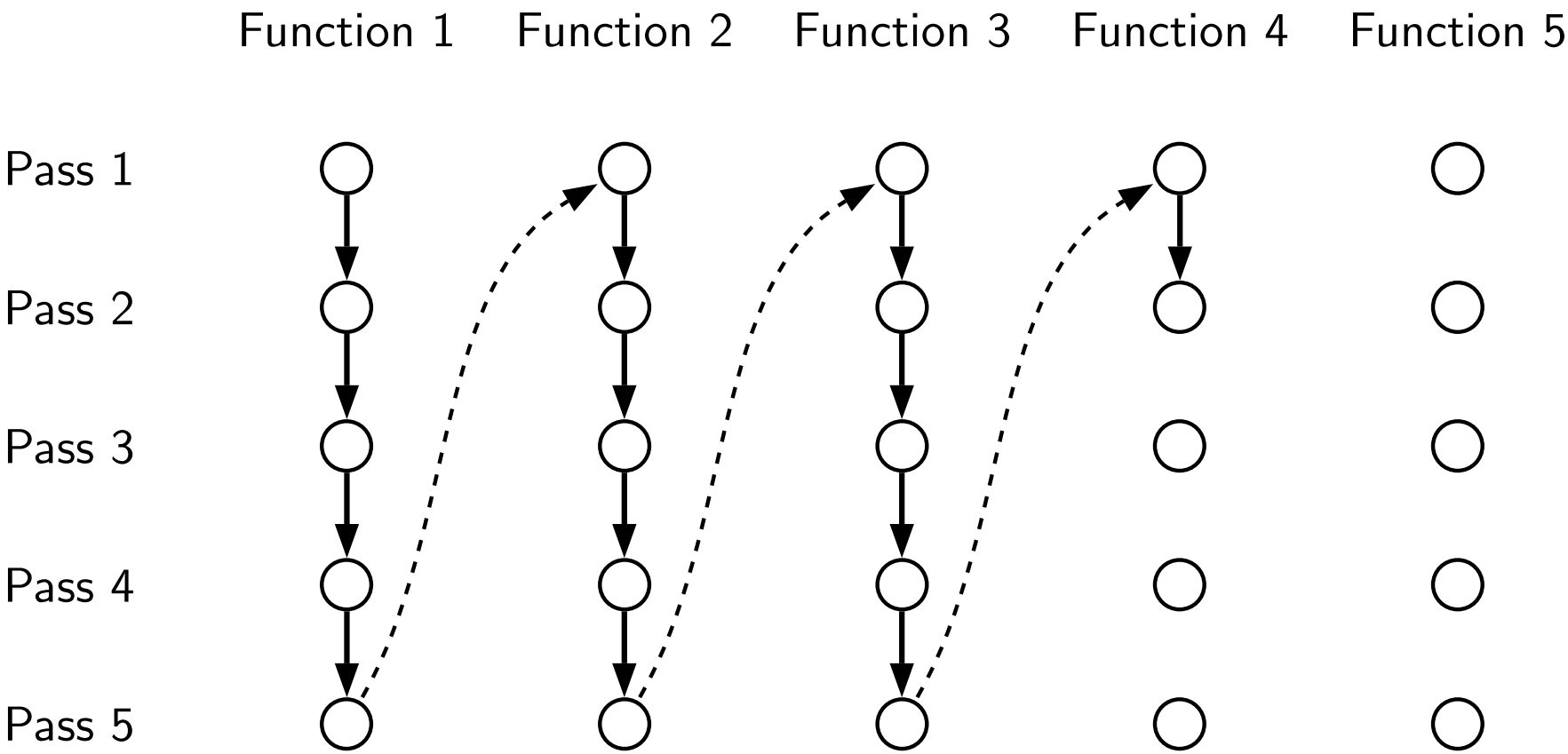

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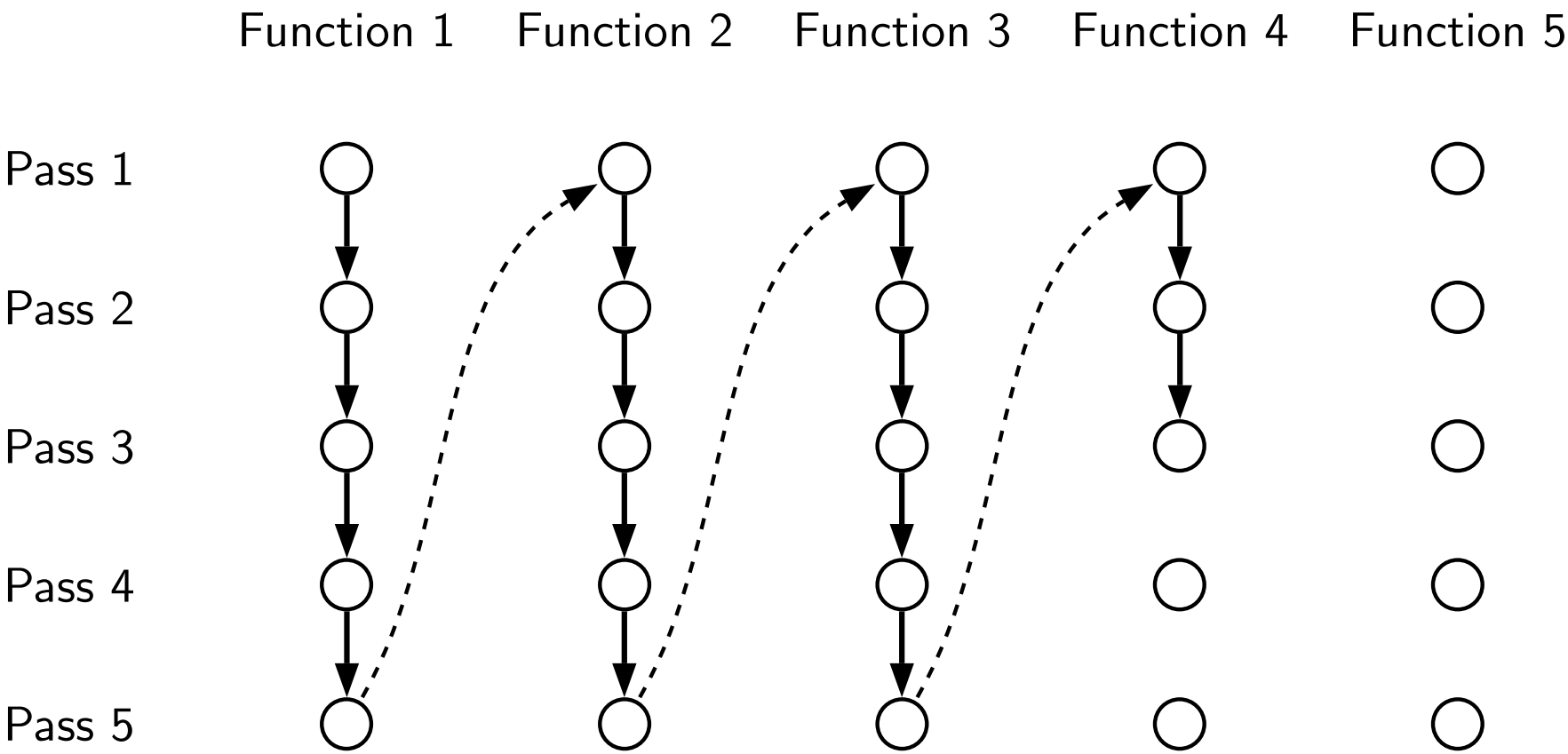

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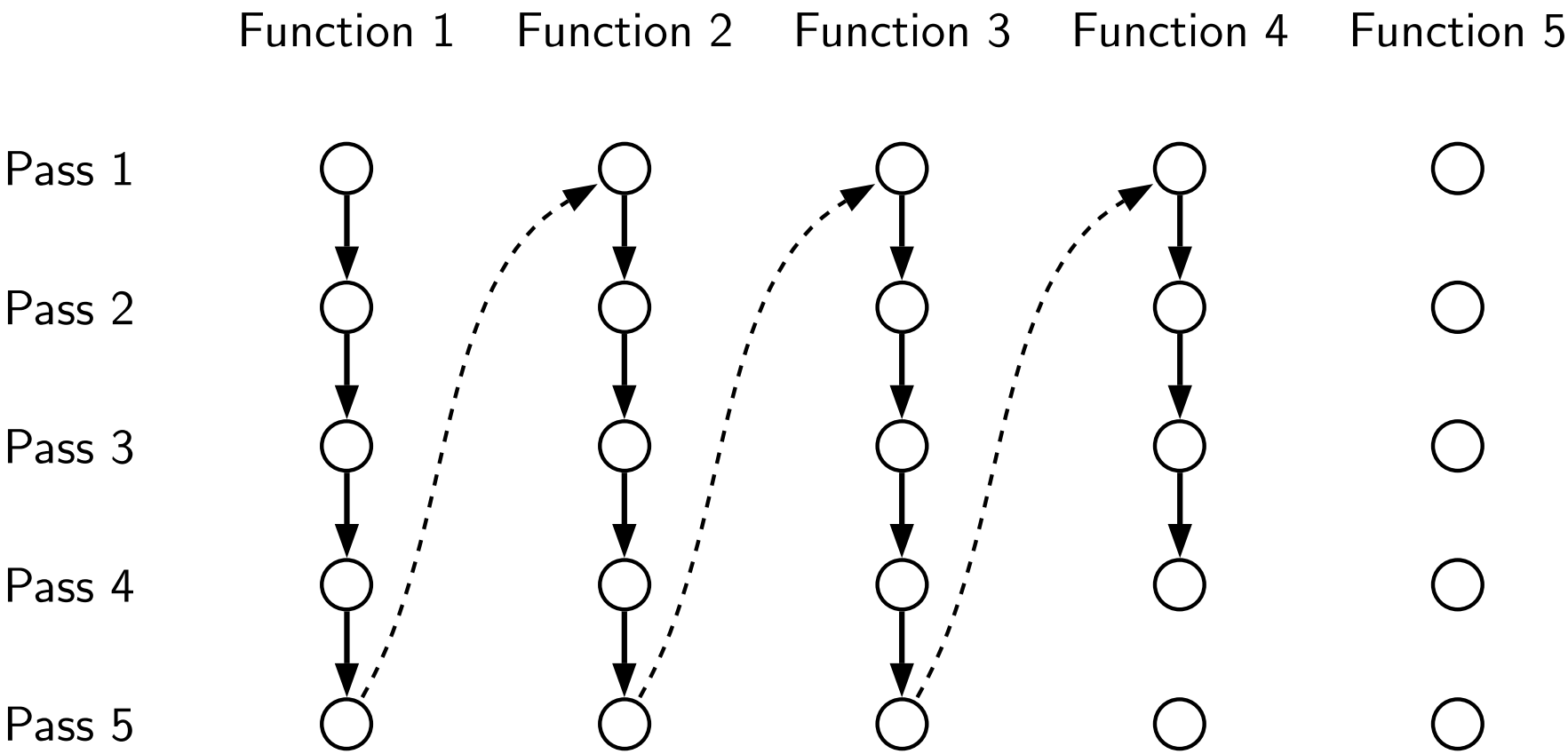

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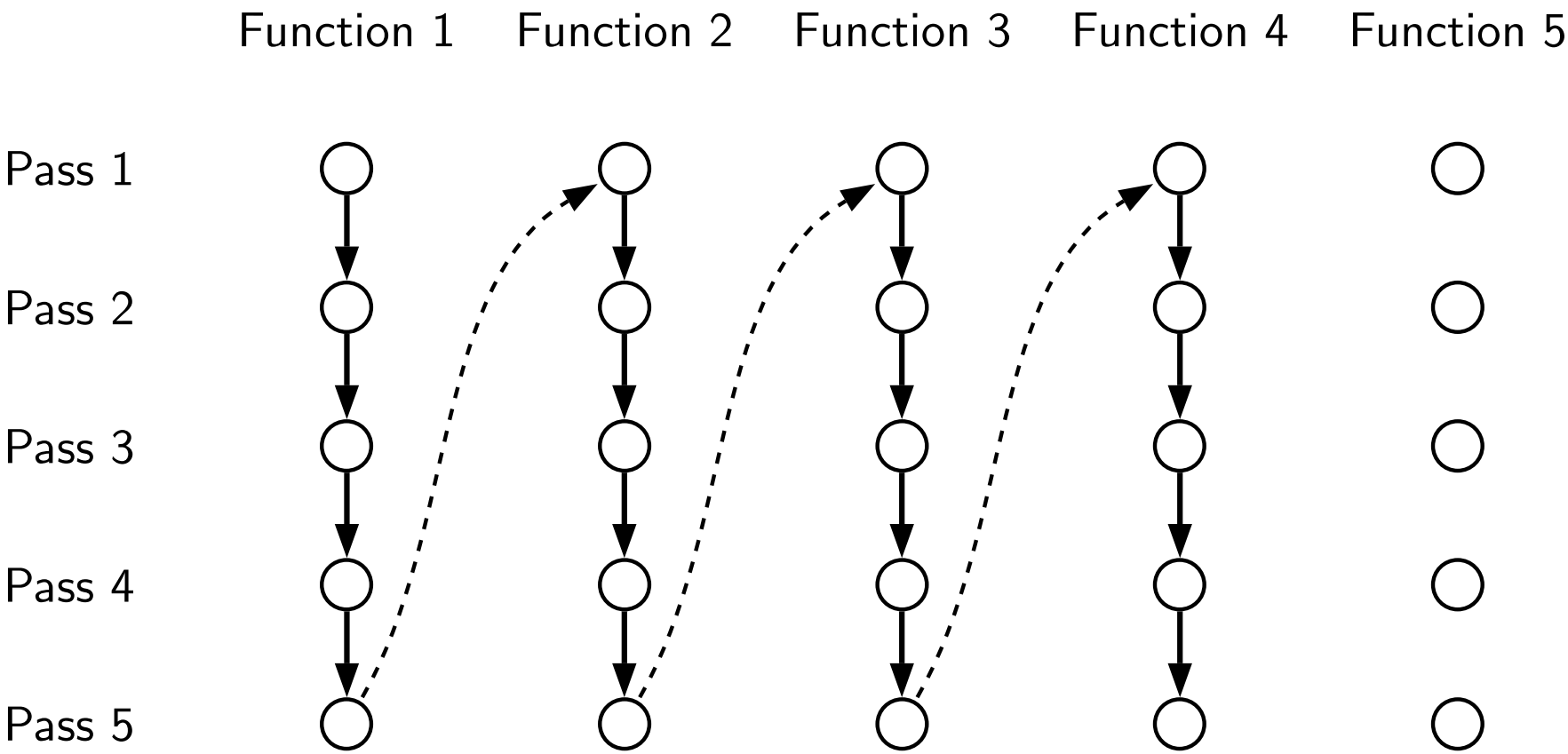

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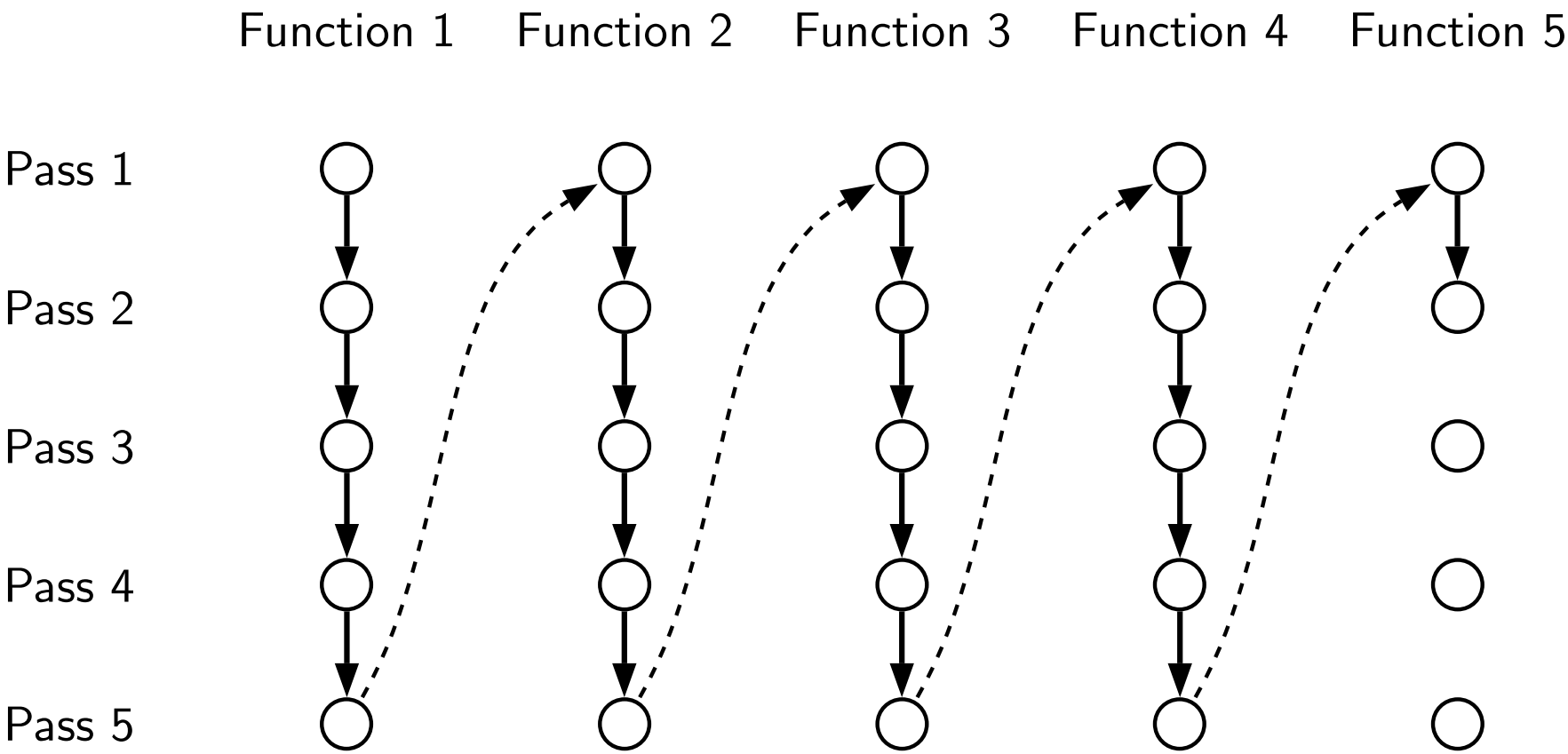

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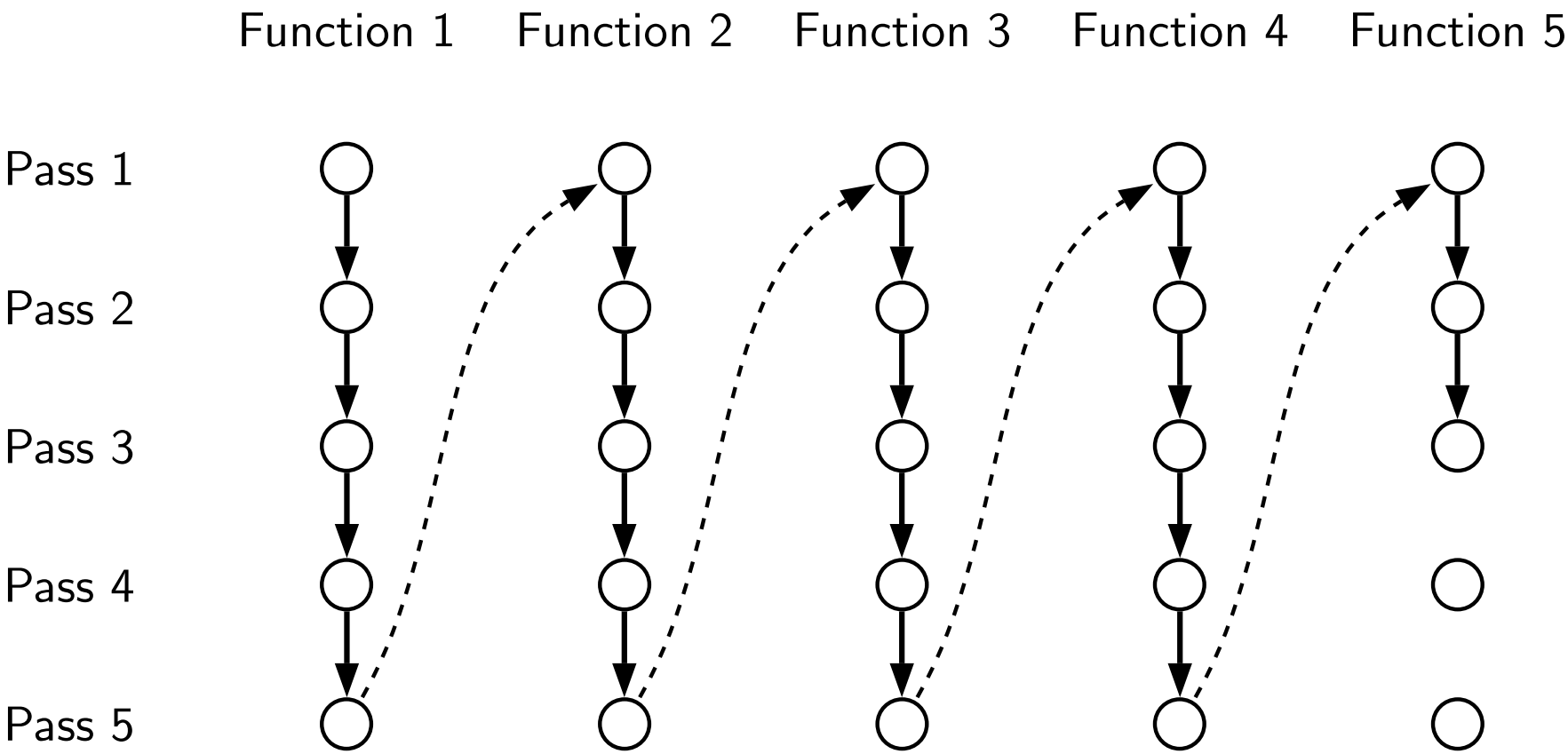

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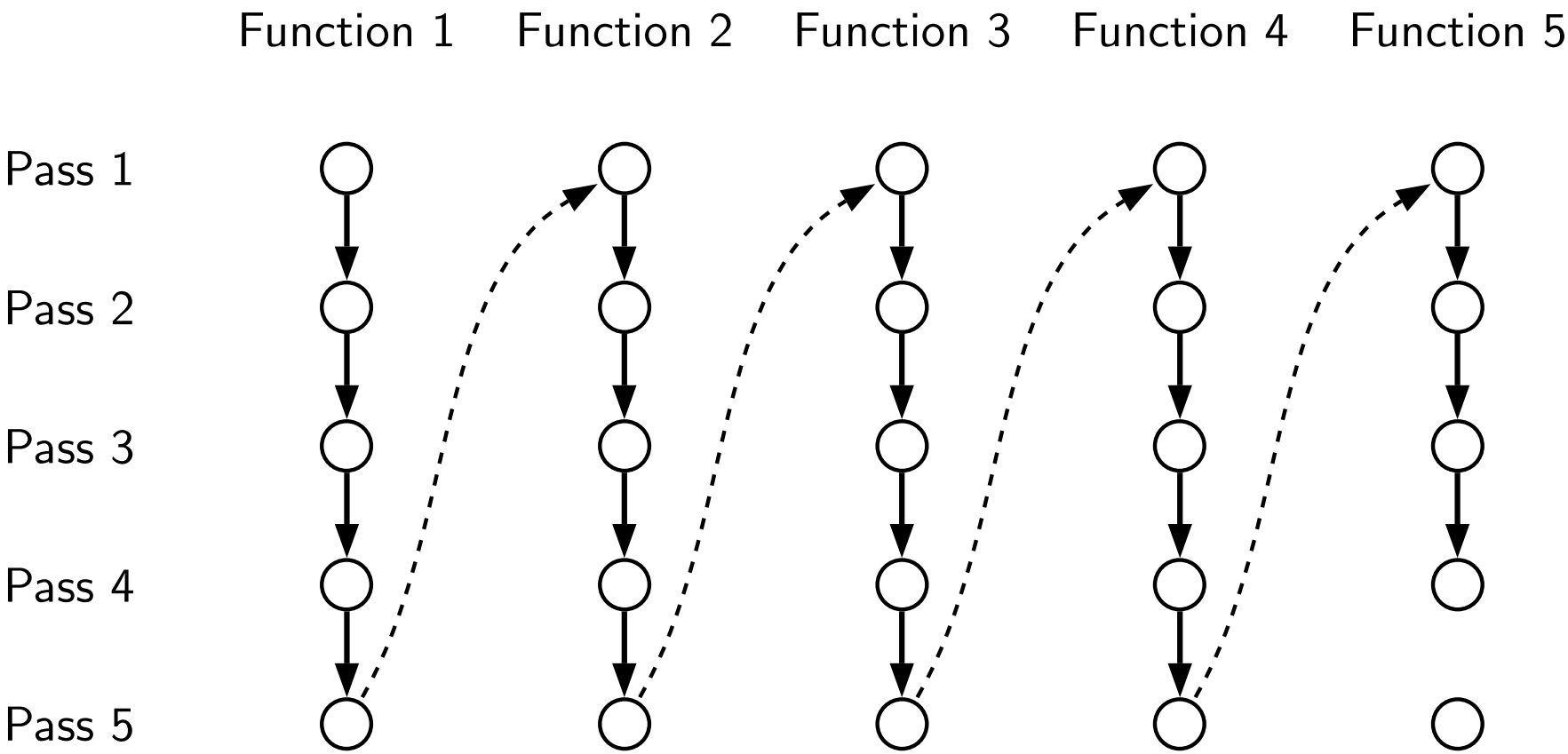

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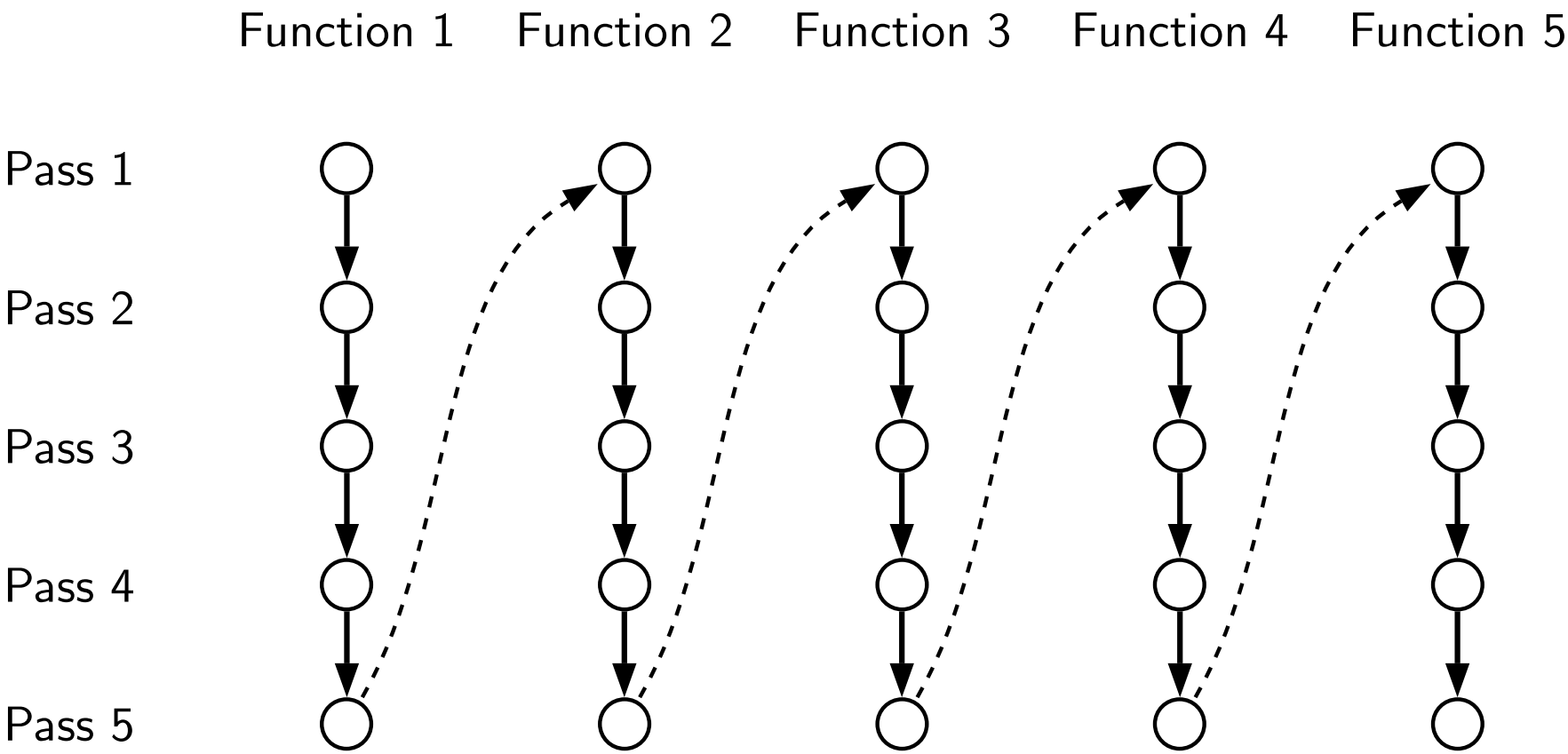
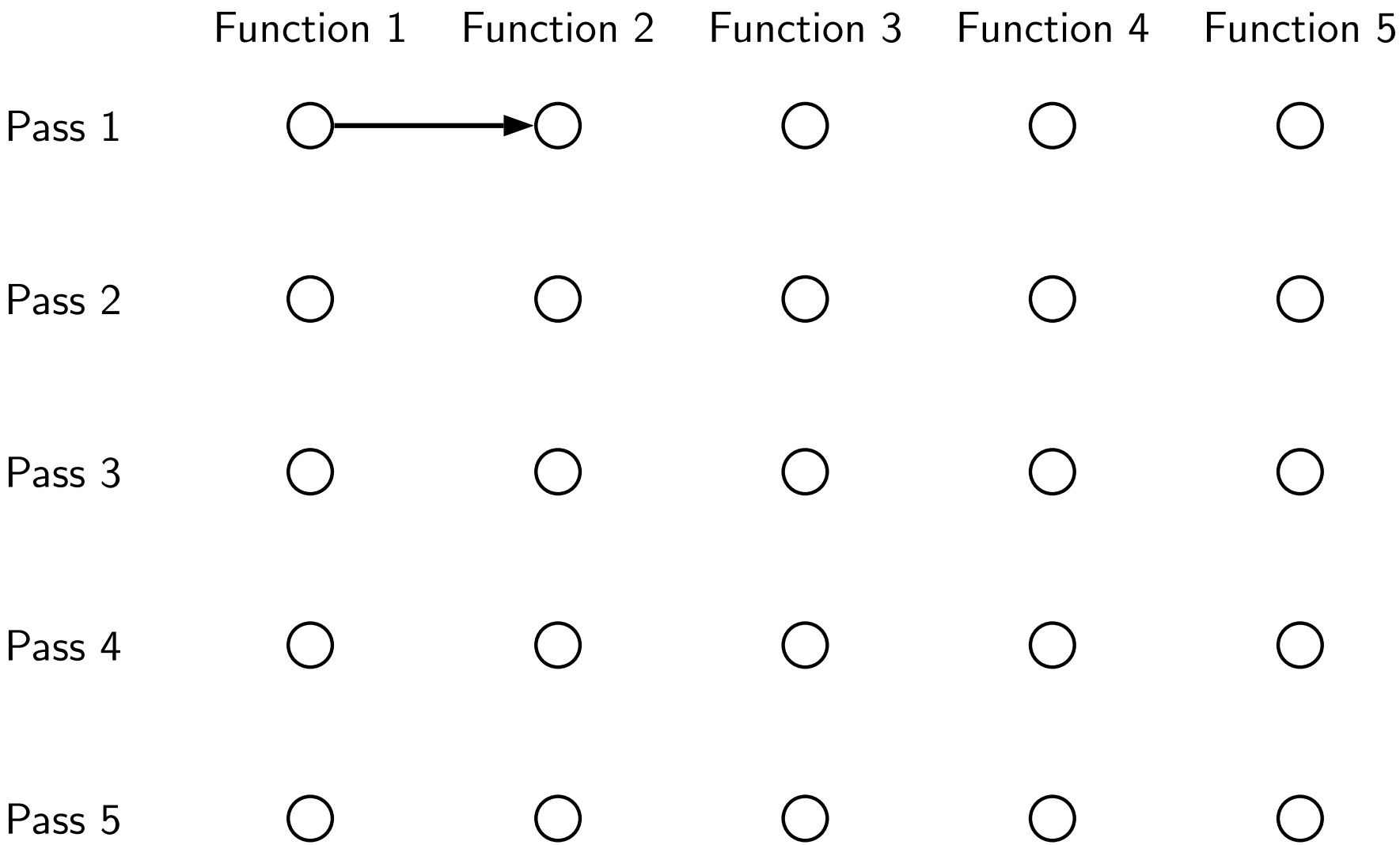


Execution Order in Interprocedural Passes

	Function 1	Function 2	Function 3	Function 4	Function 5
Pass 1	○	○	○	○	○
Pass 2	○	○	○	○	○
Pass 3	○	○	○	○	○
Pass 4	○	○	○	○	○
Pass 5	○	○	○	○	○

Execution Order in Interprocedural Passes



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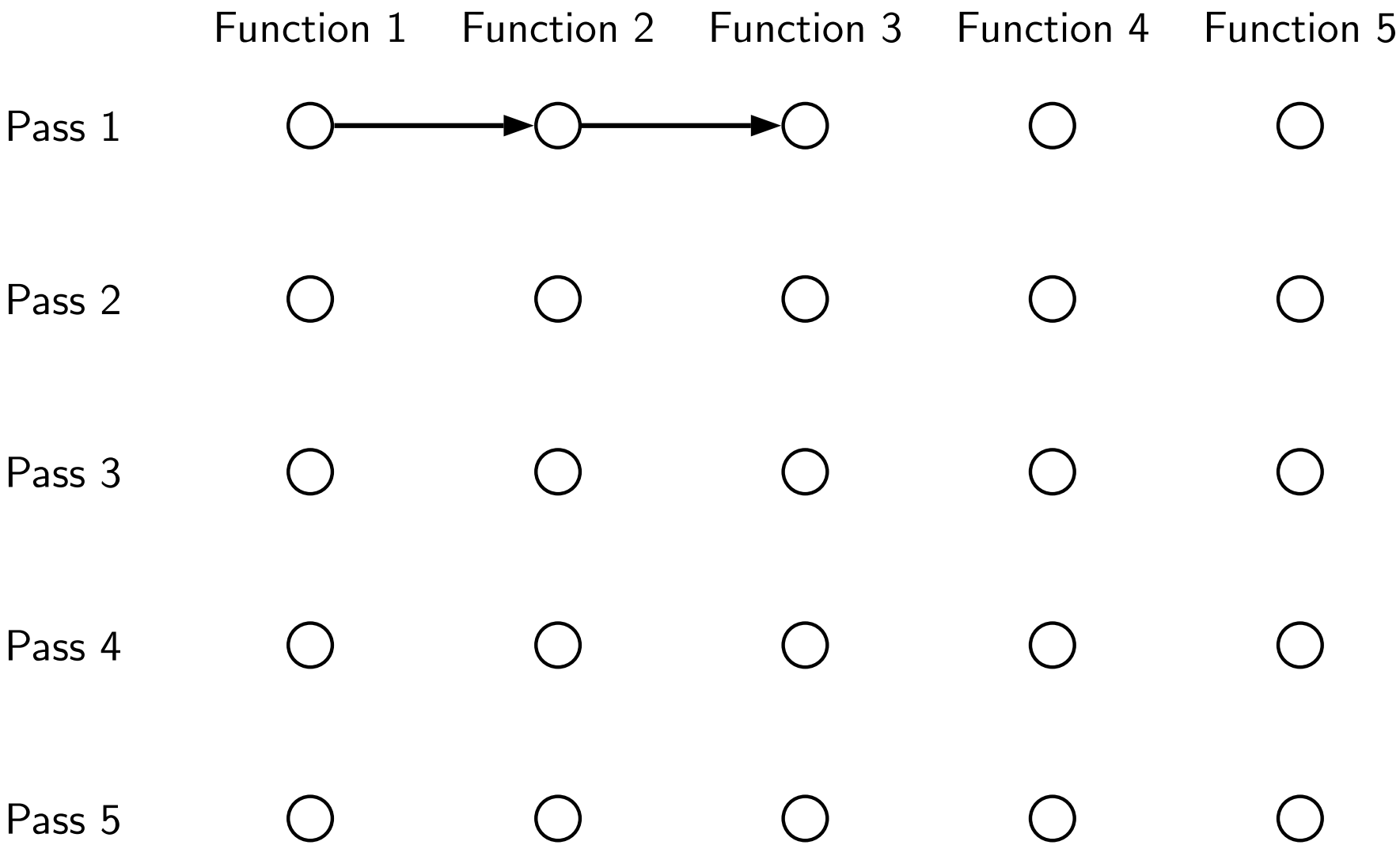

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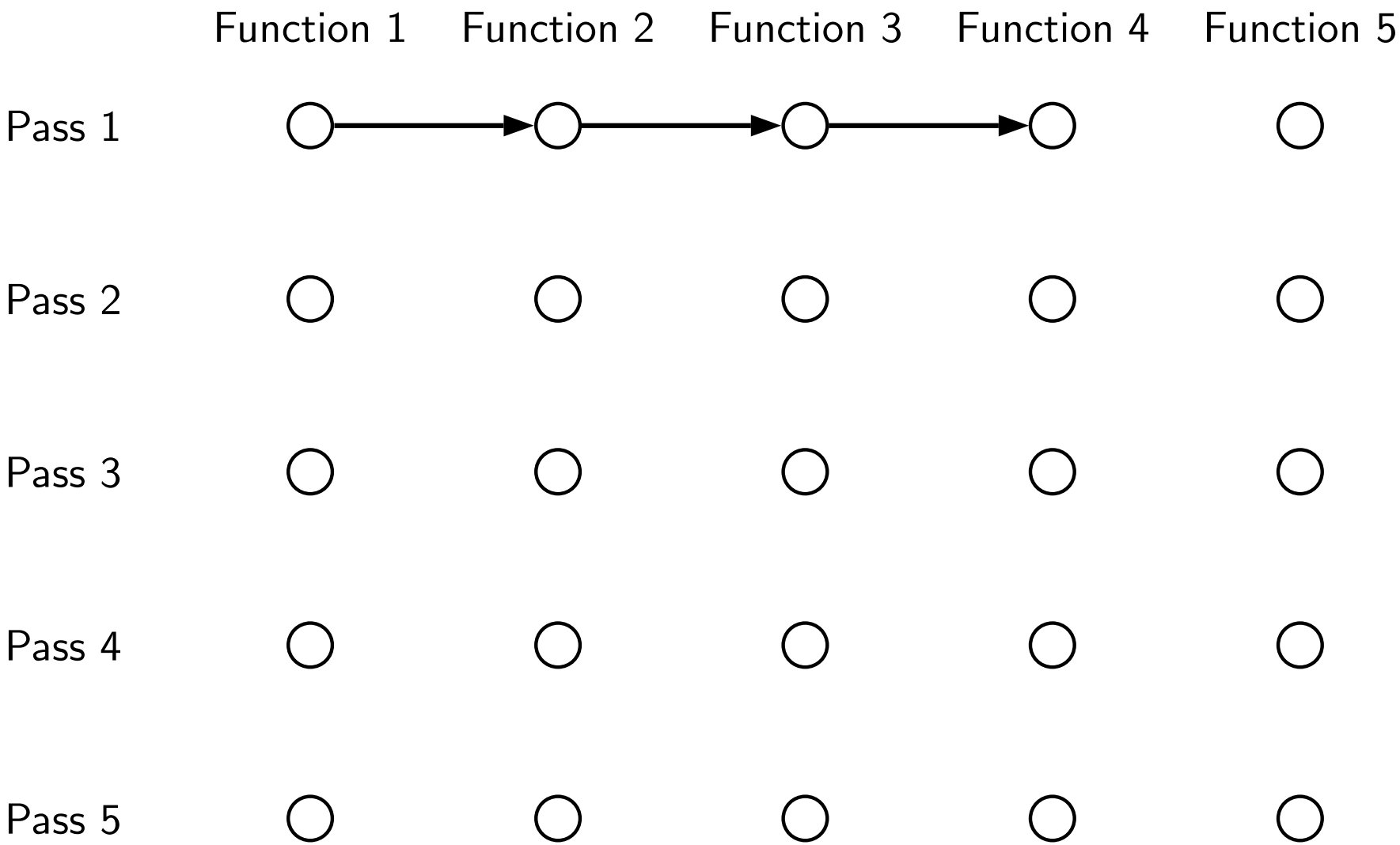

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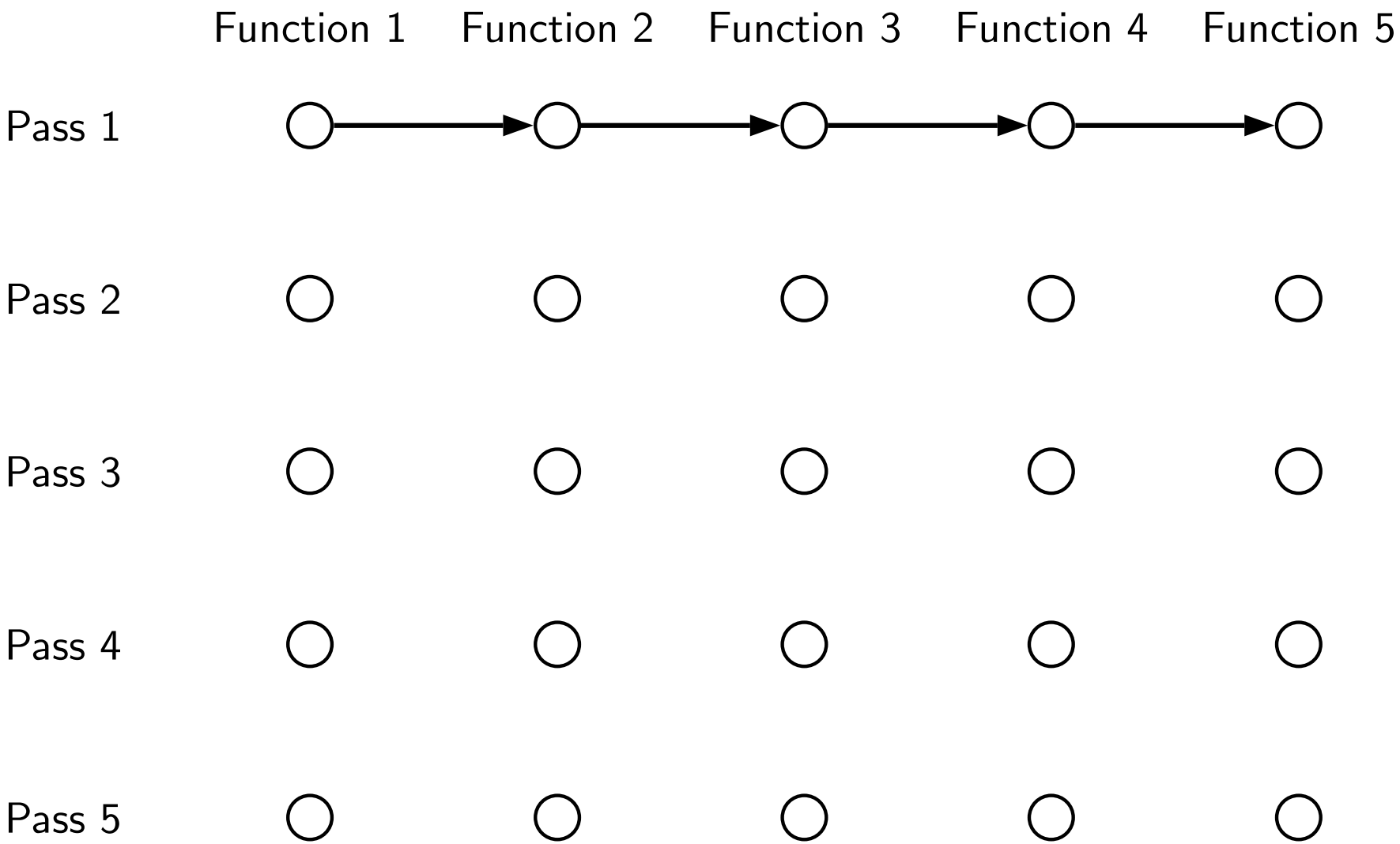

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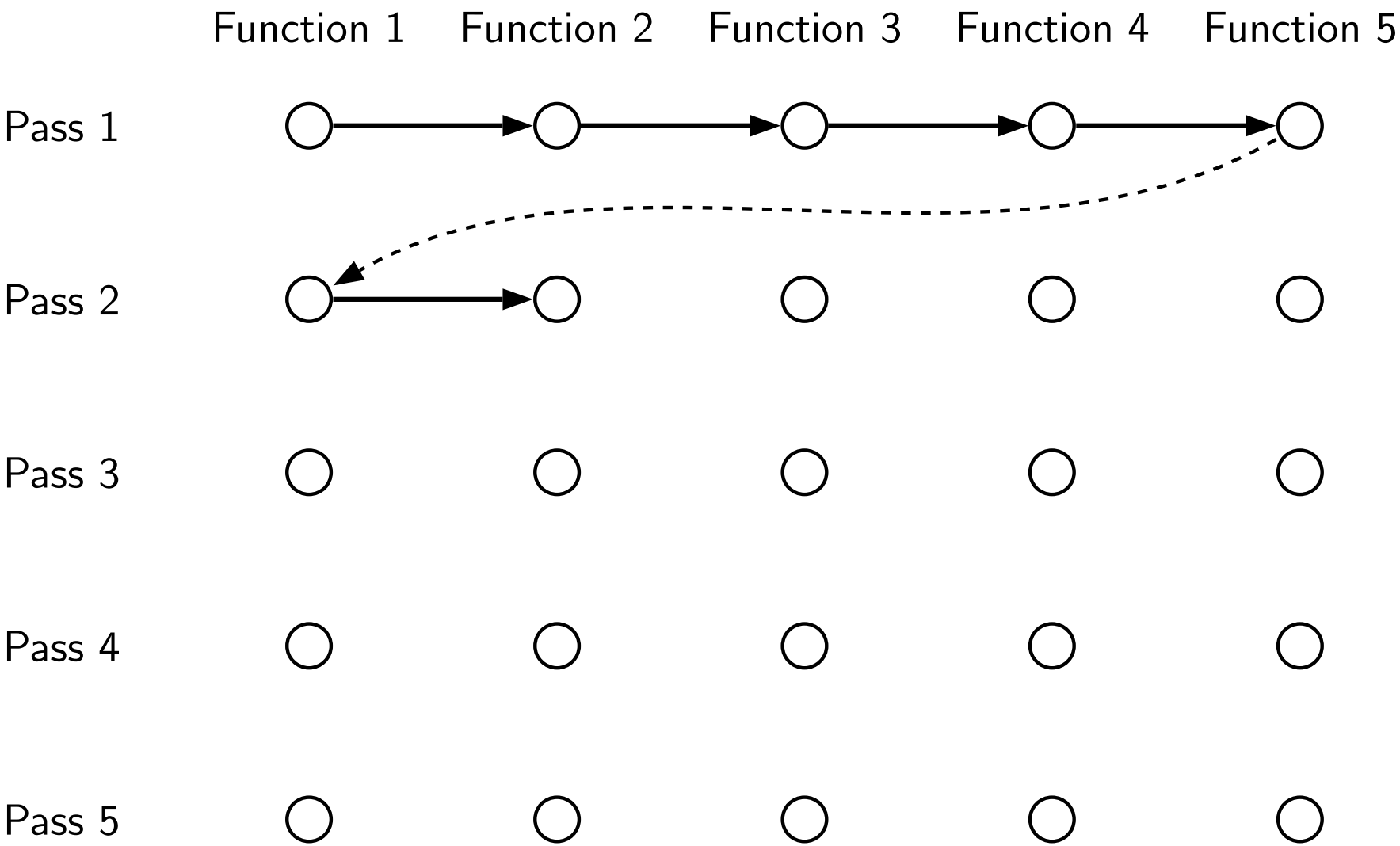

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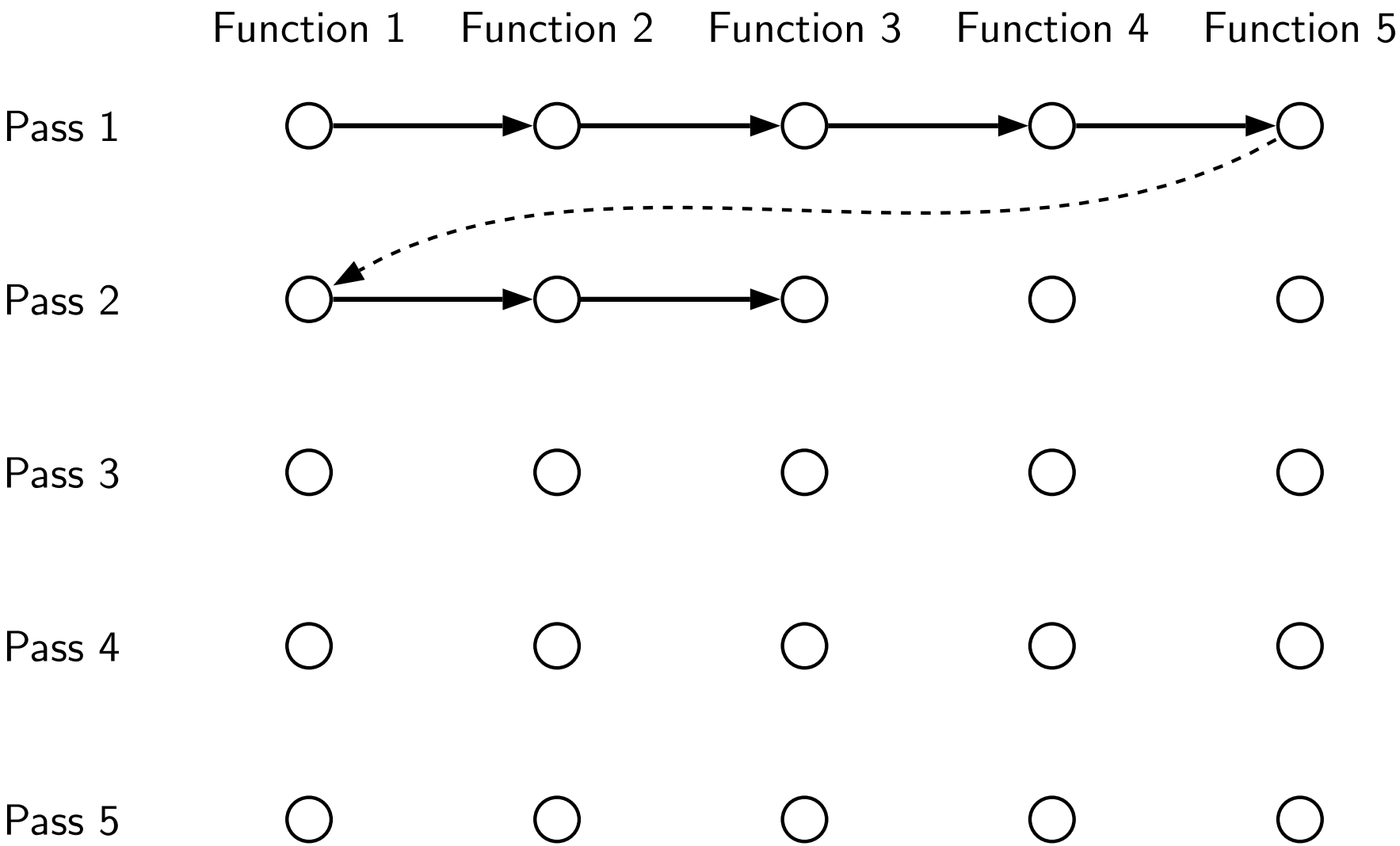

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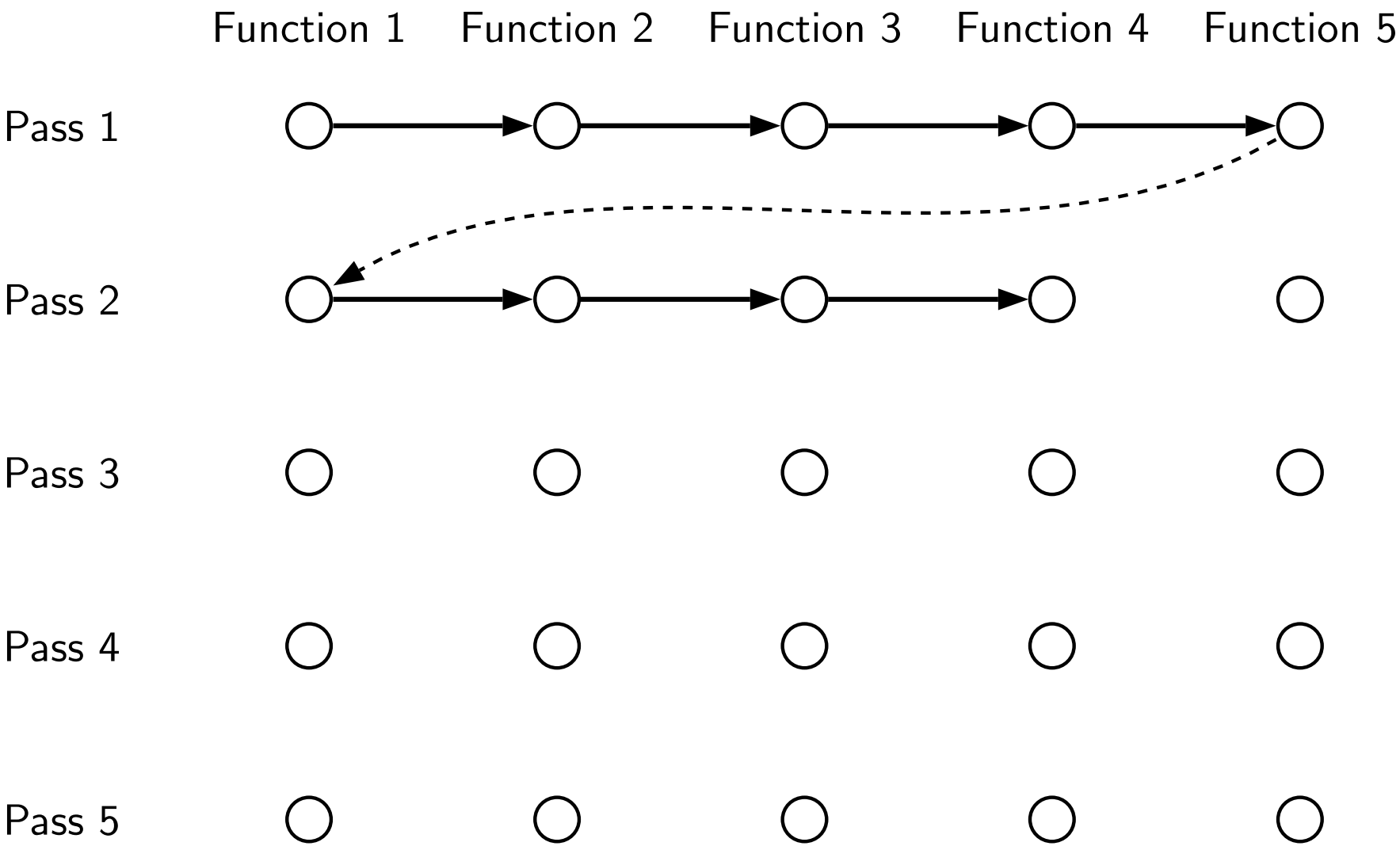

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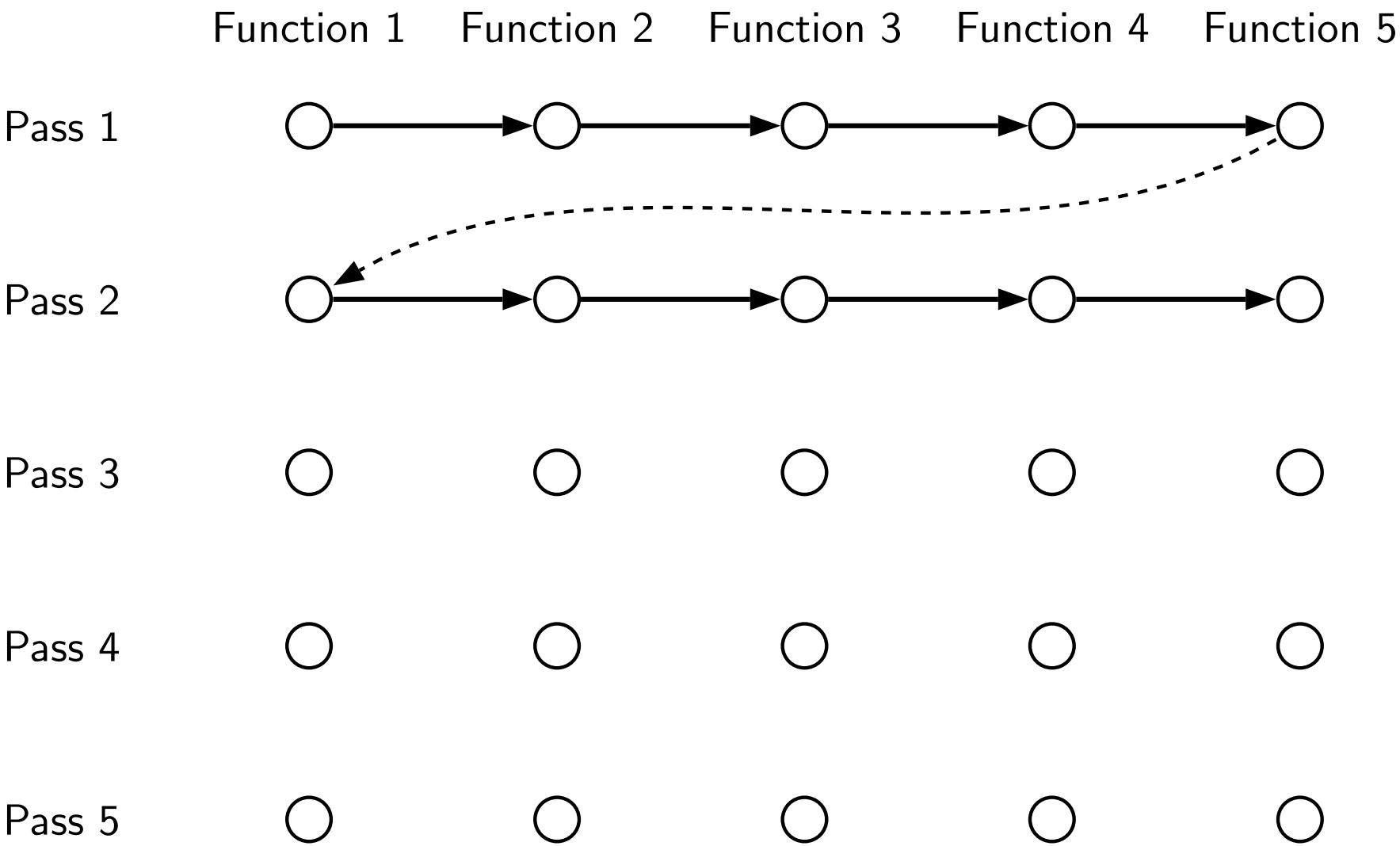

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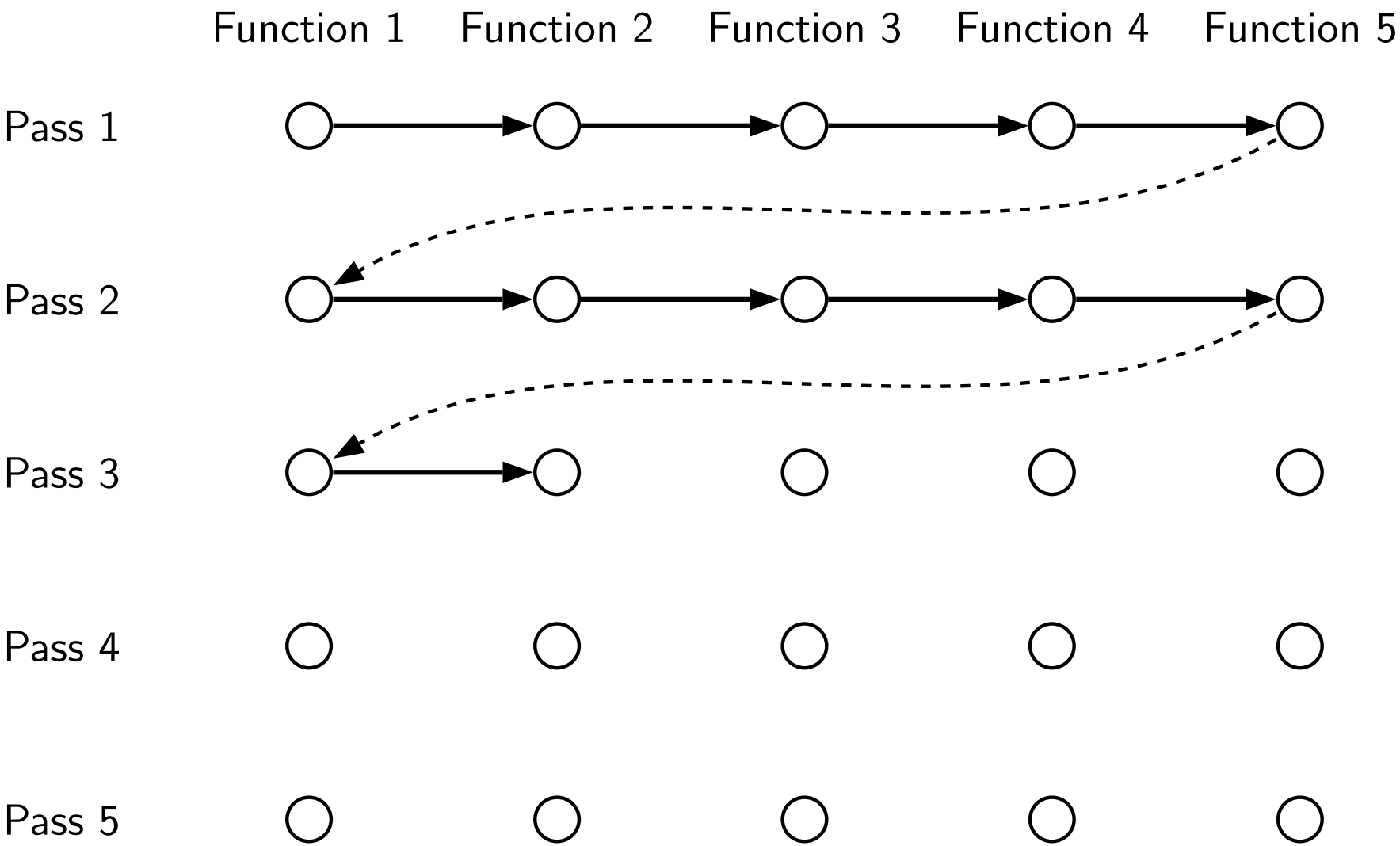

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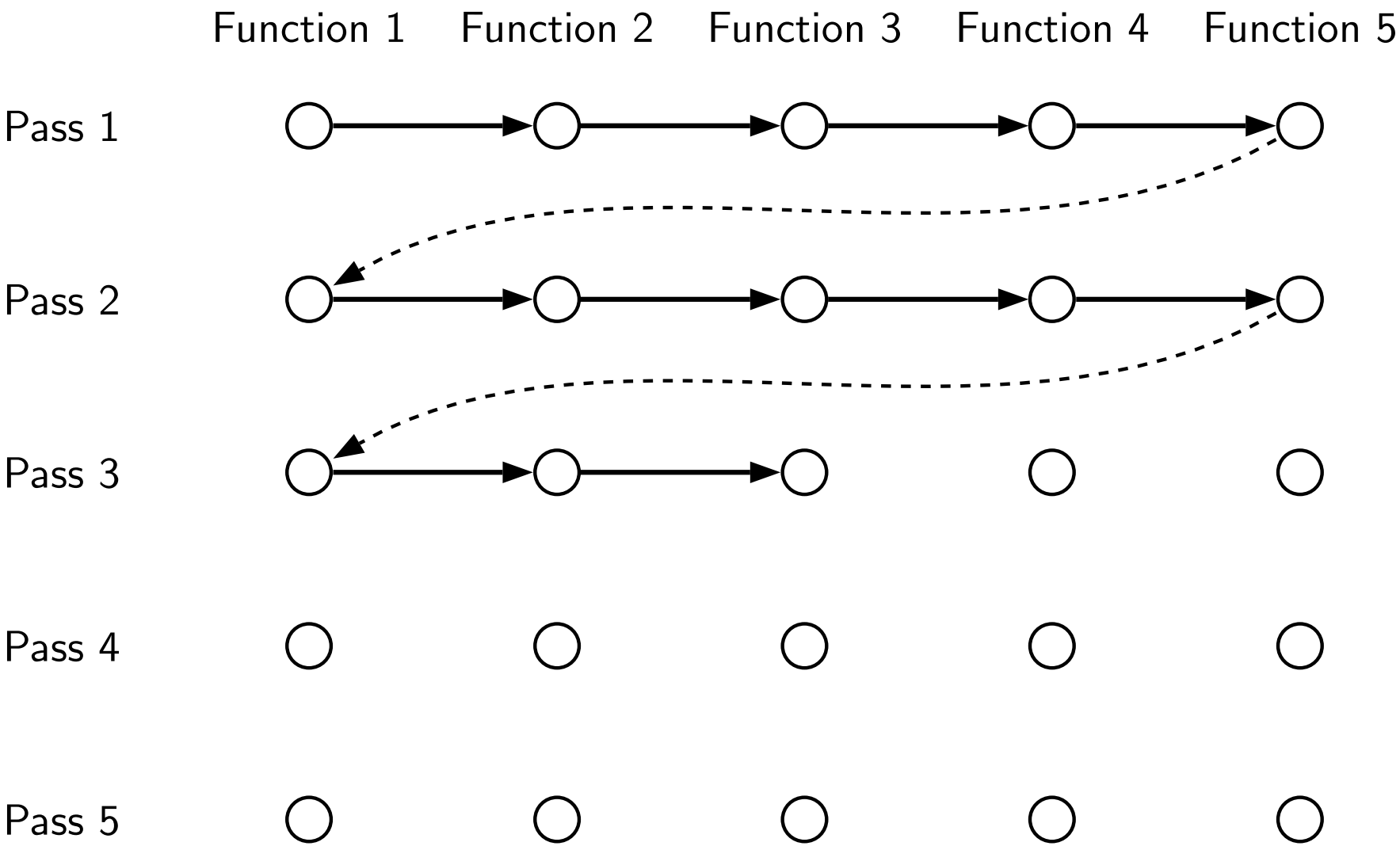

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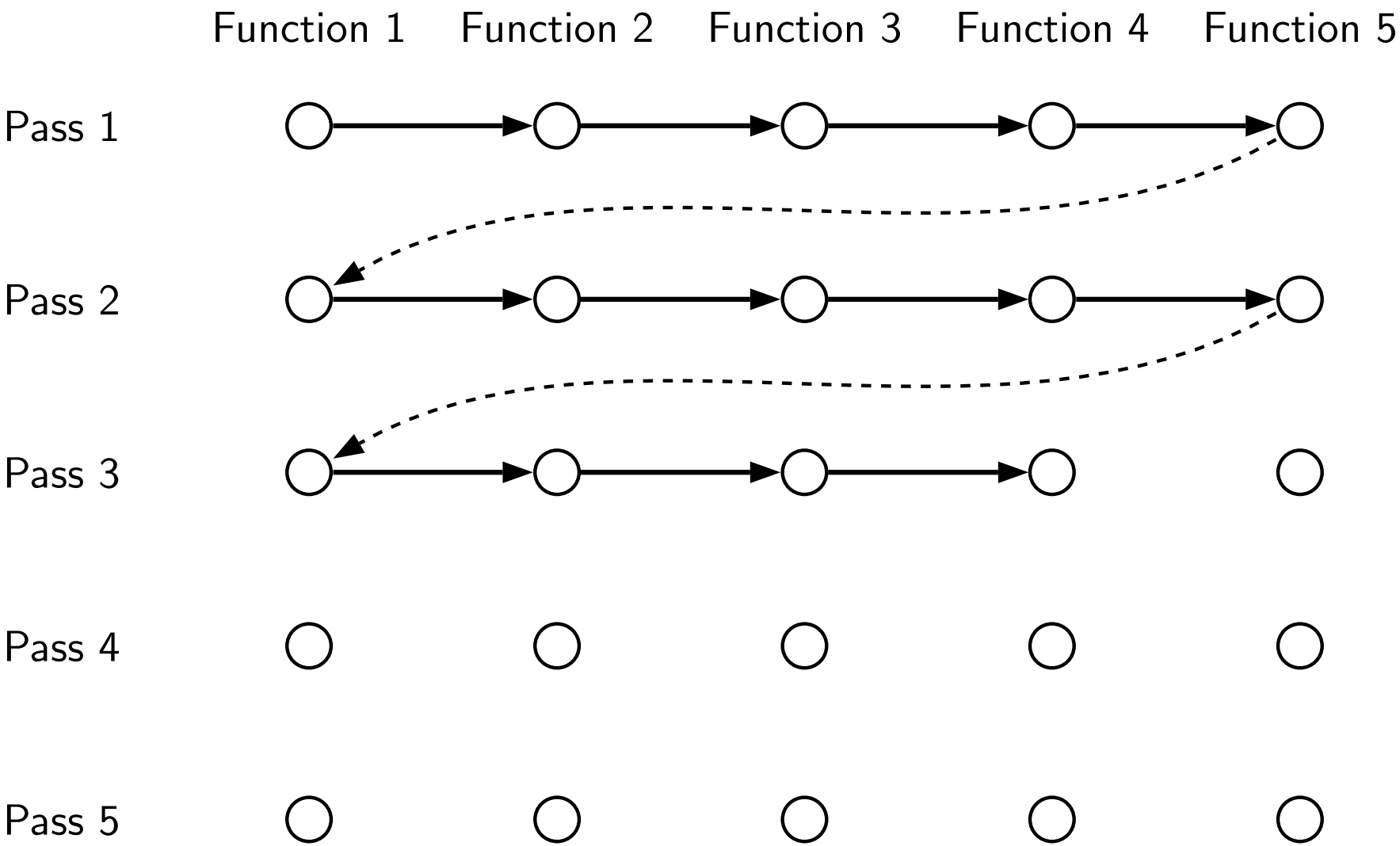
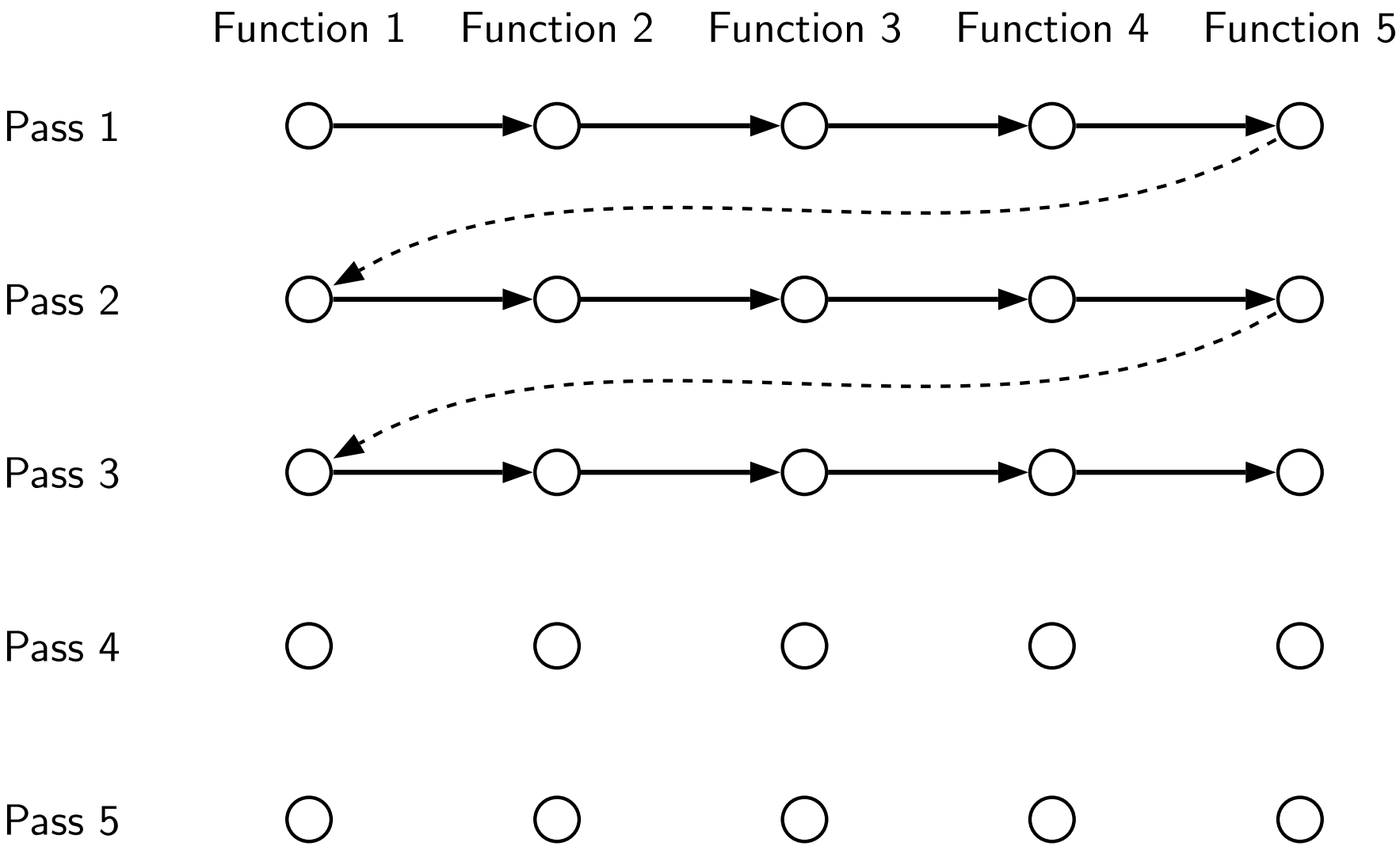


Execution Order in Interprocedural Passes



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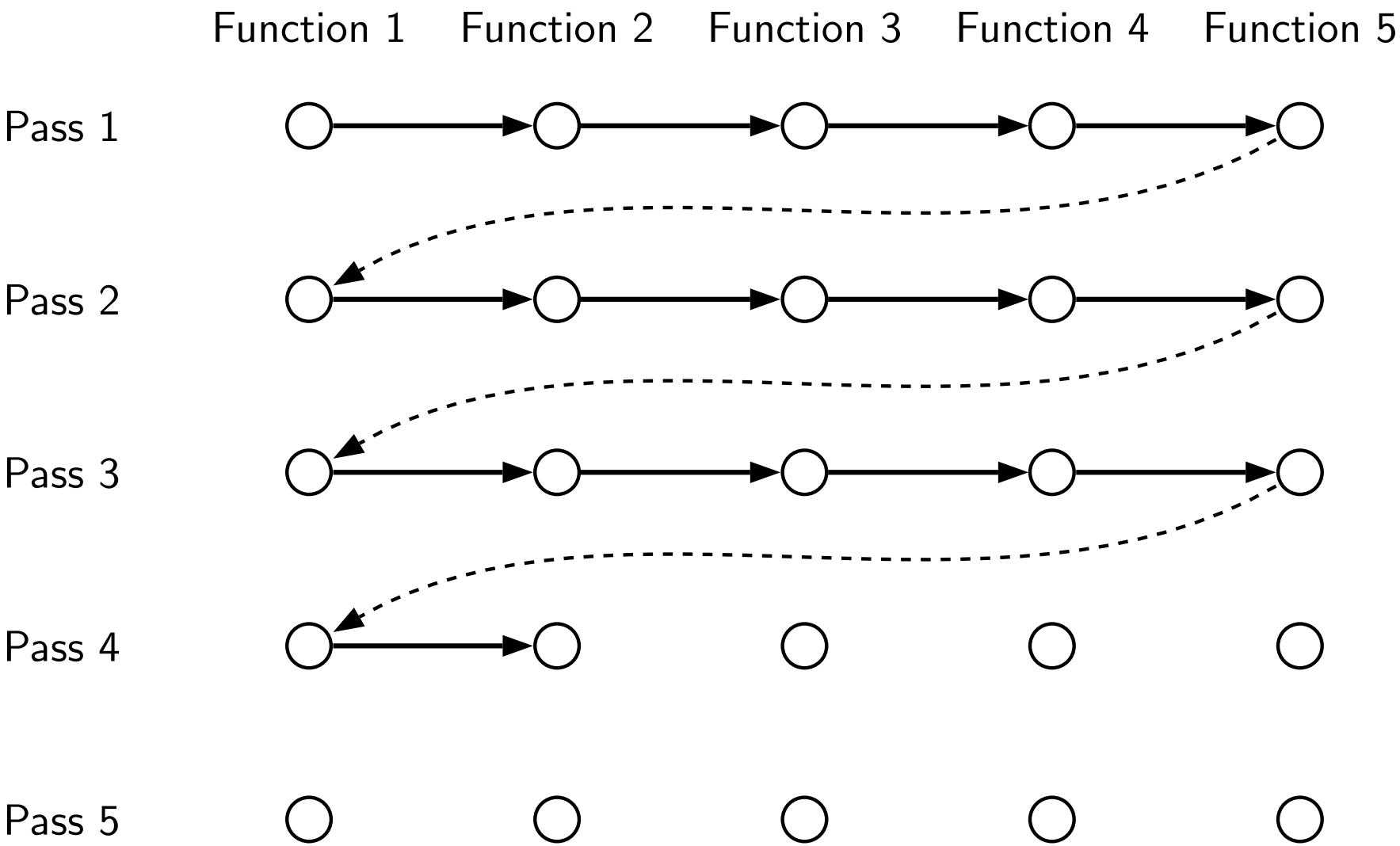

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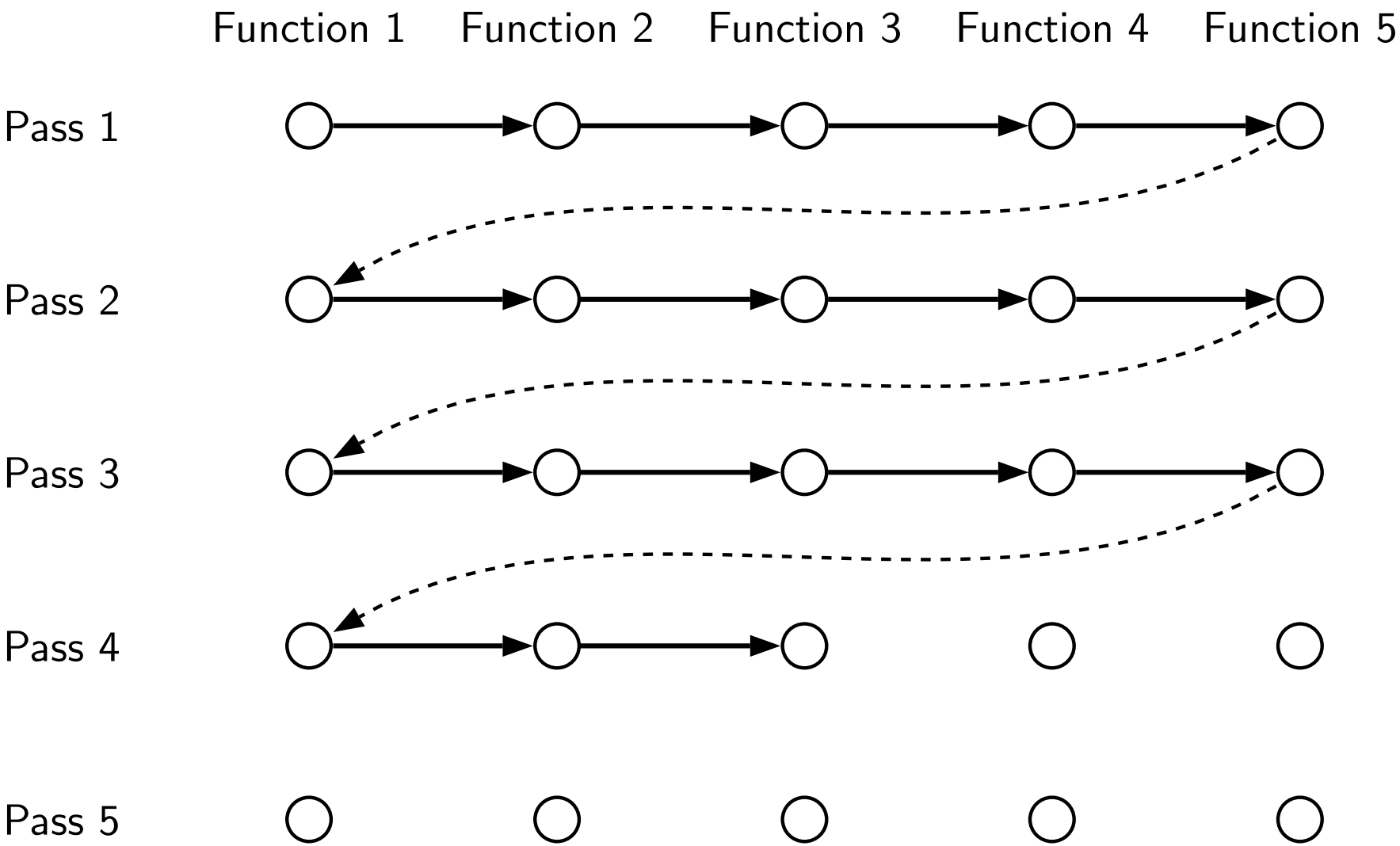
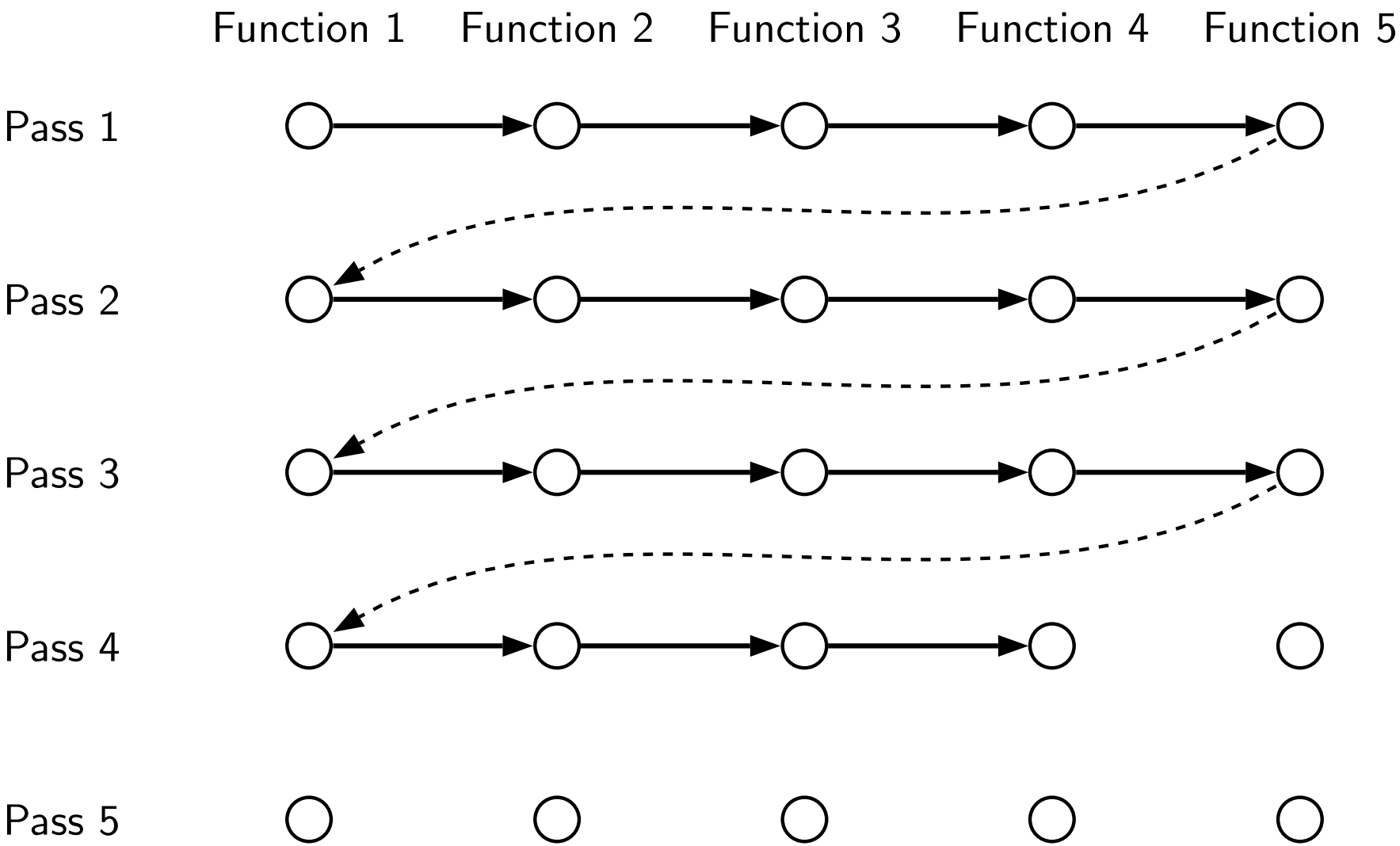


Execution Order in Interprocedural Passes



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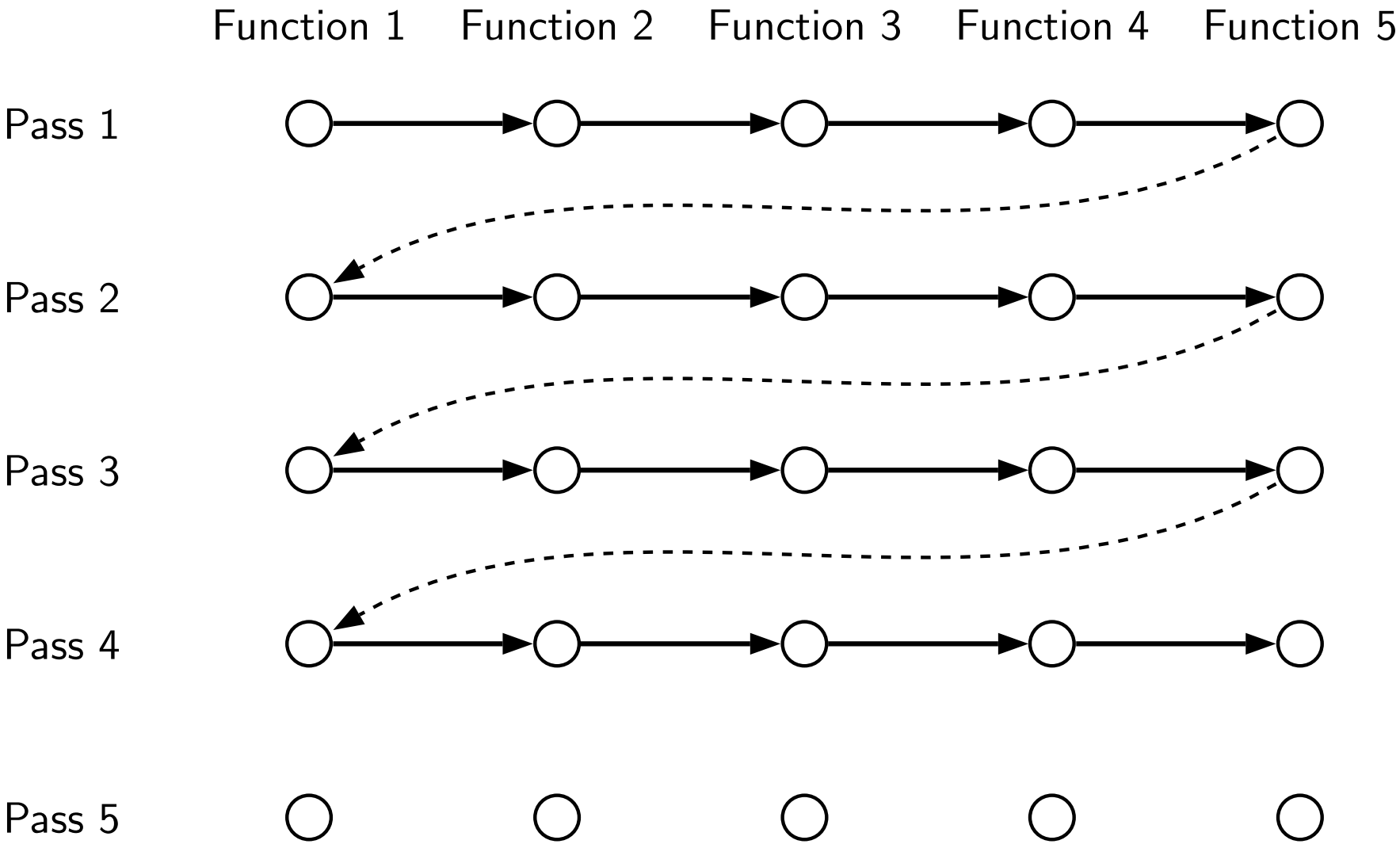
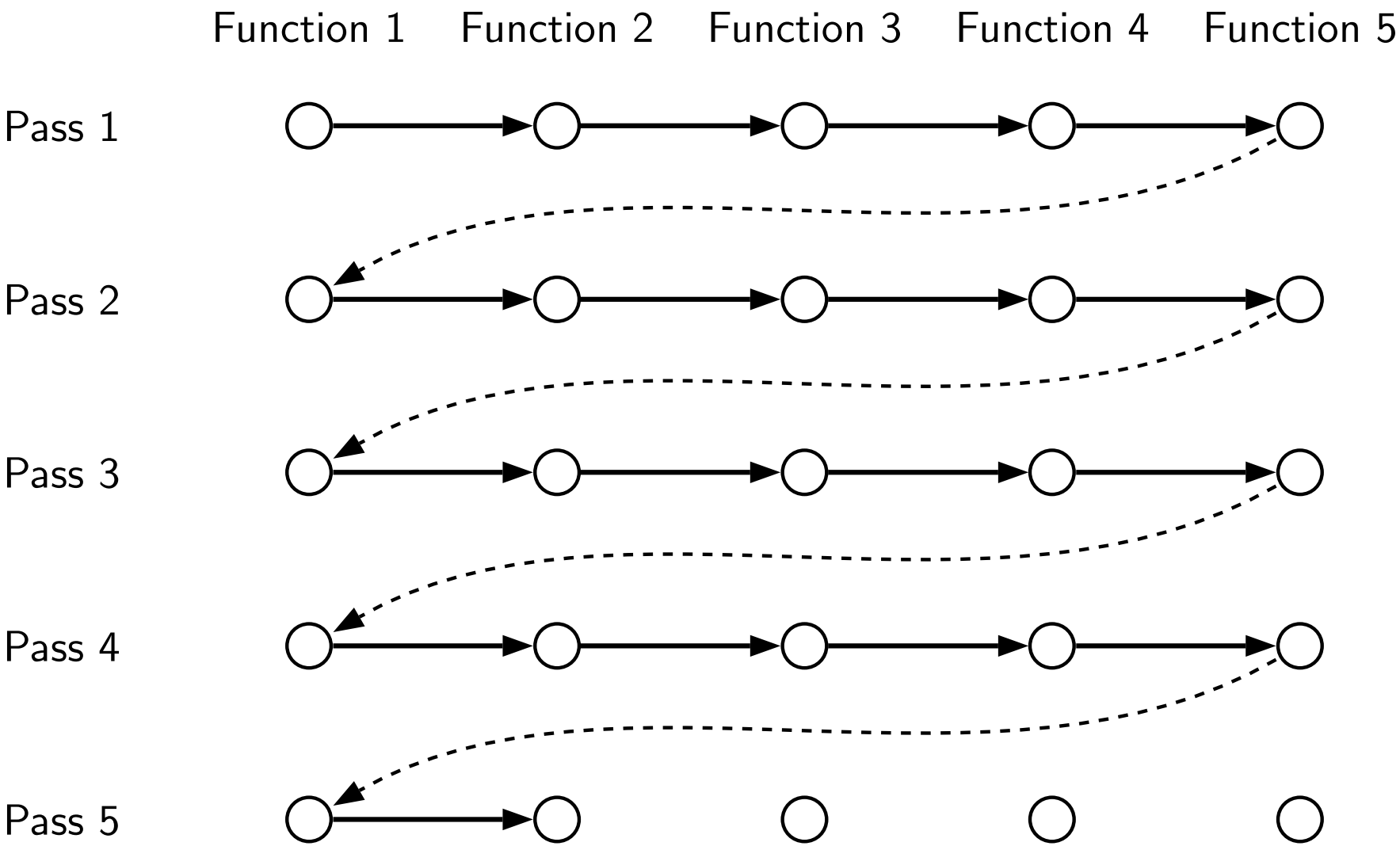
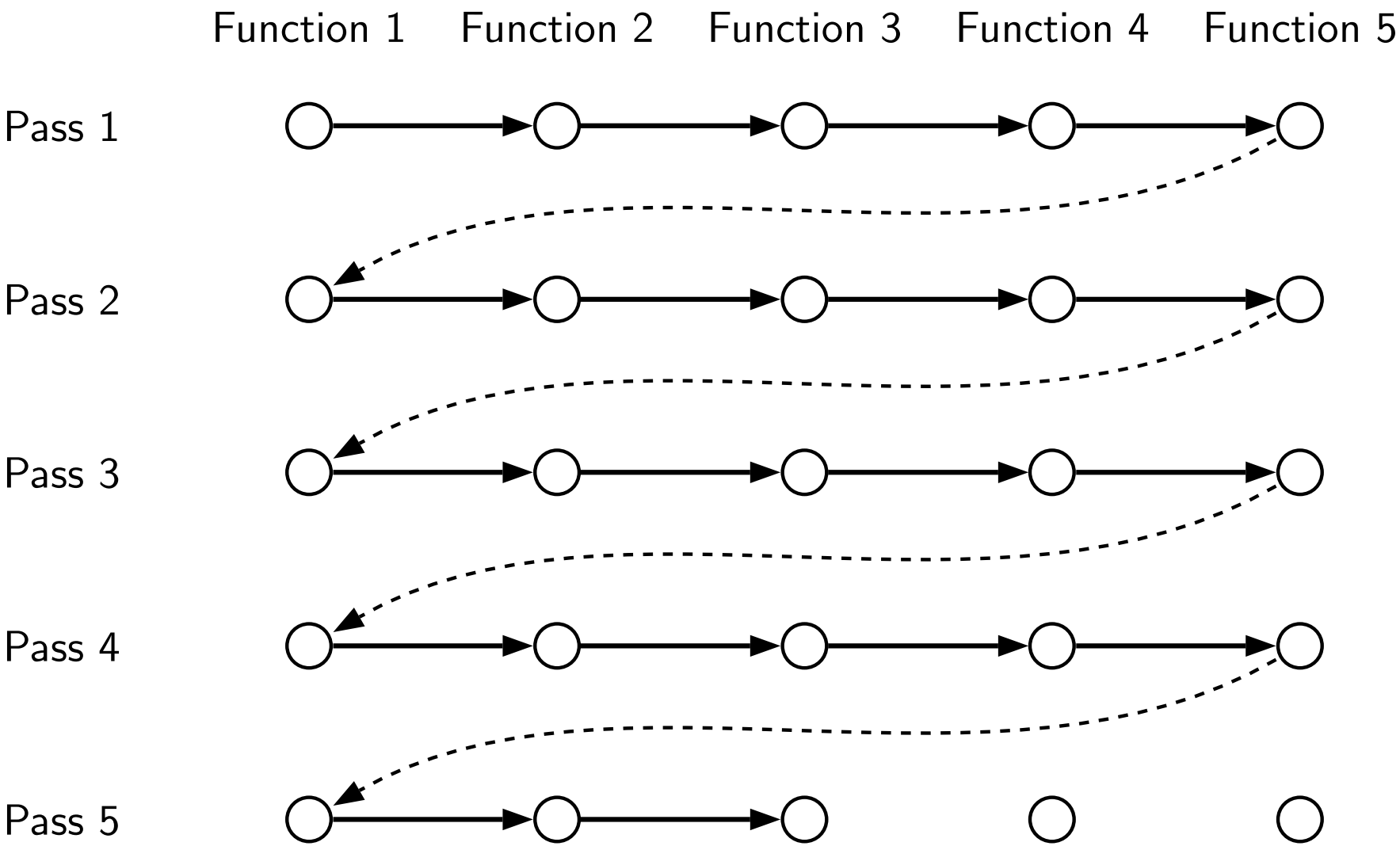


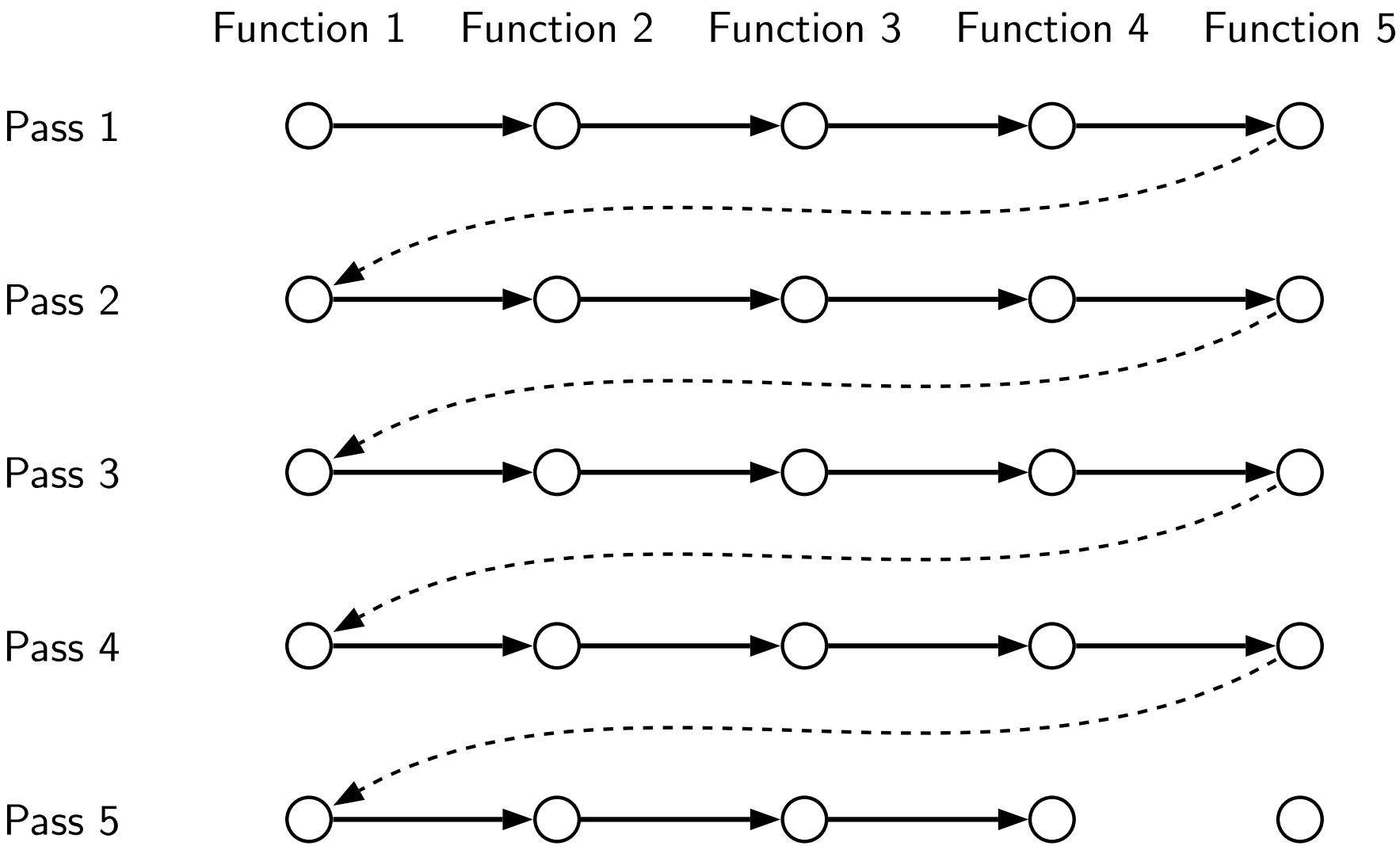
Execution Order in Interprocedural Passes



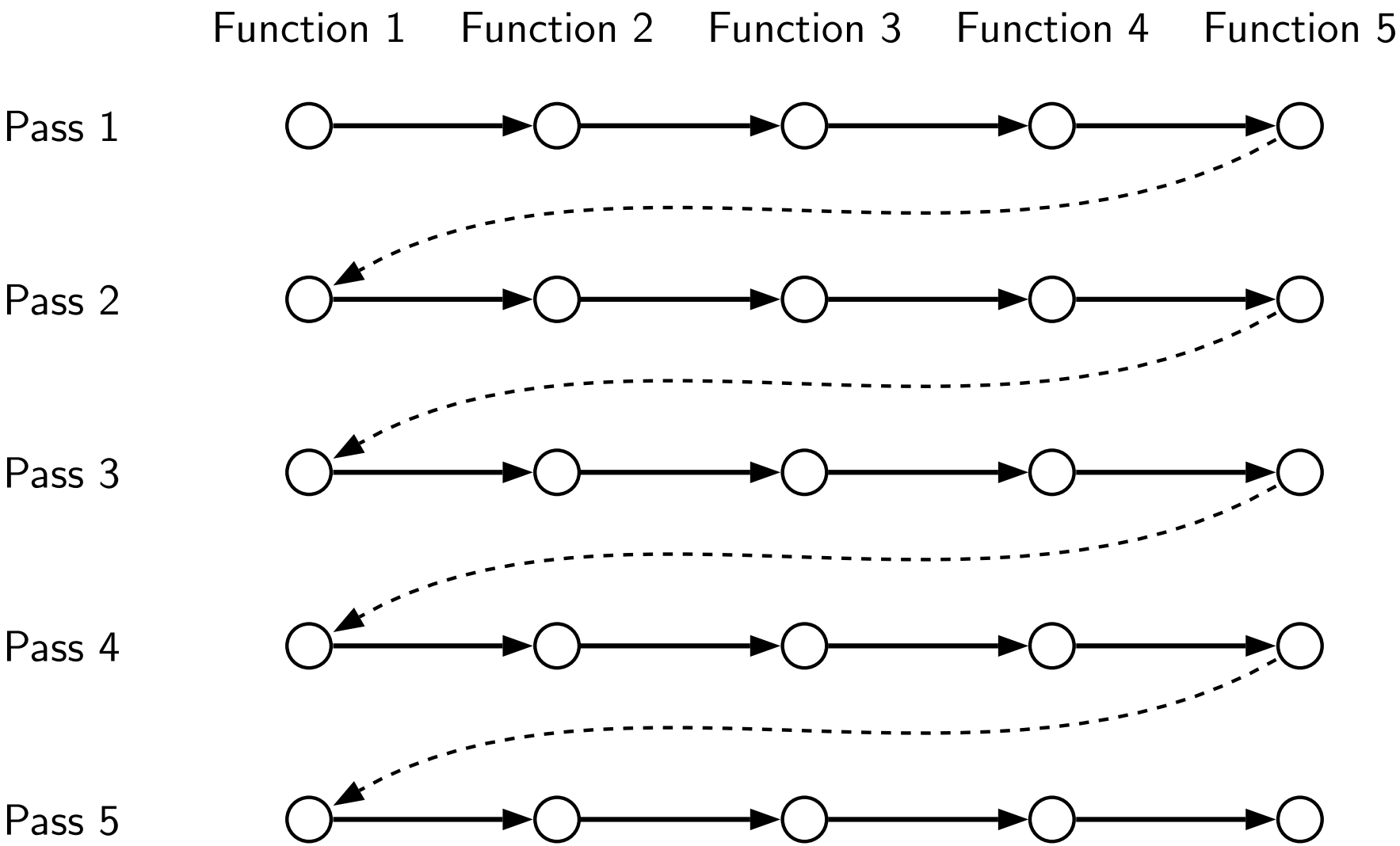
Execution Order in Interprocedural Passes



Execution Order in Interprocedural Passes



Execution Order in Interprocedural Passes



cc1 Control Flow: GIMPLE to RTL Expansion (pass_expand)

```
gimple_expand_cfg
   expand_gimple_basic_block(bb)
      expand_gimple_cond(stmt)
      expand_gimple_stmt(stmt)
         expand_gimple_stmt_1 (stmt)
            expand_expr_real_2
               expand_expr   /* Operands */
                  expand_expr_real
               optab_for_tree_code
               expand_binop /* Now we have rtx for operands */
                  expand_binop_directly
                    /* The plugin for a machine */
                    code=optab_handler(binoptab,mode);
                    GEN_FCN
                    emit_insn
```

cc1 Control Flow: GIMPLE to RTL Expansion (pass_expand)

```
gimple_expand_cfg
    expand_gimple_basic_block(bb)
        expand_gimple_cond(stmt)
        expand_gimple_stmt(stmt)
            expand_gimple_stmt_1 (stmt)
                expand_expr_real_2
                    expand_expr   /* Operands */
                        expand_expr_real
                    optab_for_tree_code
                    expand_binop /* Now we have rtx for operands */
                        expand_binop_directly
                          /* The plugin for a machine */
                          code=optab_handler(binoptab,mode);
                          GEN_FCN
                          emit_insn
```


Part 5

Link Time Optimization

Motivation for Link Time Optimization

- Default `cgraph` creation is restricted to a translation unit (i.e. a single file)
  $\Rightarrow$ Interprocedural analysis and optimization is restricted to a single file
- All files (or their equivalents) are available only at link time
  (assuming static linking)
- LTO enables interprocedural optimizations across different files

Link Time Optimization

- LTO framework supported from GCC-4.6.0
- Use `-flto` option during compilation
- Generates conventional `.o` files with GIMPLE level information inserted
  Complete translation is performed in this phase
- During linking all object modules are put together and `lto1` is invoked
- `lto1` re-executes optimization passes from the function `cgraph_optimize`

Basic Idea: Provide a larger call graph to regular ipa passes

Understanding LTO Framework

```
main ()
{
     printf ("hello, world\n");
}
```

Assembly Output without LTO Information (1)

```
        .file "t0.c"
        .section .rodata
.LC0:
        .string "hello, world"
        .text
        .globl main
        .type main, @function
main:
.LFB0:
        .cfi_startproc
        pushl %ebp
        .cfi_def_cfa_offset 8
        .cfi_offset 5, -8
        movl %esp, %ebp
        .cfi_def_cfa_register 5
        andl $-16, %esp
        subl $16, %esp
        movl $.LC0, (%esp)
        call puts
        leave
        .cfi_restore 5
        .cfi_def_cfa 4, 4
        ret
        .cfi_endproc
.LFE0:
        .size main, .-main
        .ident "GCC: (GNU) 4.7.2"
        .section .note.GNU-stack,"",@pro
```


Assembly Output with LTO Information (2)

```
.ascii "\b"
.text
.section  .gnu.lto_.refs.57f4e8b14959f6c4,"",@progbits
.string "x\234cb‘d‘f‘‘‘b\200\001"
.string ""
.string "\204"
.ascii "\t"
.text
.section .gnu.lto_.statics.57f4e8b14959f6c4,"",@progbits
.string "x\234cb‘d‘b\300\016@\342\214\020&"
.string ""
.string "\375"
.ascii "\t"
.text
.section  .gnu.lto_.decls.57f4e8b14959f6c4,"",@progbits
.string "x\234\215R=O\002A\020\2359Ne\303IB!\201\n\032M\224h\374\0
.string "\3218\311\313\275\333\233\2317\363n5@\020q@p(\2565\200E\3
.string "\2004\370!\336mB\003~\2068\017\022tB\230‘\020\232\2046\24
.string "\022Z\023\372\b\345\247\261^\t\270\341v\357\355\210\307>\
```

Assembly Output with LTO Information (3)

```
.string "\3474\030\205KN\321;\346\034\367L\324\031\304\301"
.string "\3040\023\202\202\031\f\324\002&\336aT\261\"
.string "\024\313k\260\004\017\\\306 O\245\323 \375\347iWu\001\232
.string "\"\343\245\226\225\032\242\322\306\004\024]\261\244'\246"
.string "\273%\262\367P\3440\360\245A\b.8\257q~\302\263\257\341"
.string "\377\r\037\020\236h\020A\257qK-\"\277\300hO\006g\262"
.string "\347/vE^Ovc\036\032r\343\032\232\230a\324%.N\317G\006"
.string "\366\3442L\222\270\242\334Q\201\216\307\334o\207\276\342"
.string "\270%&\2661\3446E\377\037\374Q\320\364\013\"P\027\003\333
.string "\007\257\212^\335\254\252\353bD2\345\305\300\030\231\362"
.string "\273\326#\372[\0321\230\031j\204$\334Jg9\r\237\236\363\35
.string "\377\335\273%d\363\346V>\271\221J\301Teu\245"
.ascii "o\026\005\213."
.text
.section .gnu.lto_.symtab.57f4e8b14959f6c4,"",@progbits
.string "main"
.string ""
.string ""
.string ""
.string ""
```


Assembly Output with LTO Information (4)

```
        .string ""
        .string ""
        .string ""
        .string ""
        .string ""
        .string ""
        .string ""
        .string "\240"
        .string ""
        .string ""
        .text
        .section .gnu.lto_.opts,"",@progbits
        .string "'-fexceptions''-mtune=generic''-march=pentiumpro''-flto'"
        .text
        .section .rodata
.LC0:
        .string "hello, world"
```

Assembly Output with LTO Information (5)

```
        .text
        .globl main
        .type main, @function
main:
.LFB0:
        .cfi_startproc
        pushl %ebp
        .cfi_def_cfa_offset 8
        .cfi_offset 5, -8
        movl %esp, %ebp
        .cfi_def_cfa_register 5
        andl $-16, %esp
        subl $16, %esp
        movl $.LC0, (%esp)
        call puts
```


Assembly Output with LTO Information (6)

```
        leave
        .cfi_restore 5
        .cfi_def_cfa 4, 4
        ret
        .cfi_endproc
.LFE0:
        .size main, .-main
        .comm __gnu_lto_v1,1,1
        .ident "GCC: (GNU) 4.7.2"
        .section .note.GNU-stack,"",@progbits
```

Interprocedural Optimizations Using LTO

Whole program optimization needs to see the entire program

- Does it need the entire program *together* in the memory?

  Load only the call graph without function bodies

  - Independent computation of summary information of functions
  - "Adjusting" summary information through whole program analysis over the call graph
  - Perform transformation independently on functions

- Process the entire program together

Why Avoid Loading Function Bodies?

- Practical programs could be rather large and compilation could become very inefficient
- Many optimizations decisions can be taken by looking at the call graph alone
  - Procedure Inlining: just looking at the call graph is sufficient
    Perhaps some summary size information can be used
  - Procedure Cloning: some additional summary information about actual parameters of a call is sufficient

Partitioned and Non-Partitioned LTO

Load complete call graph

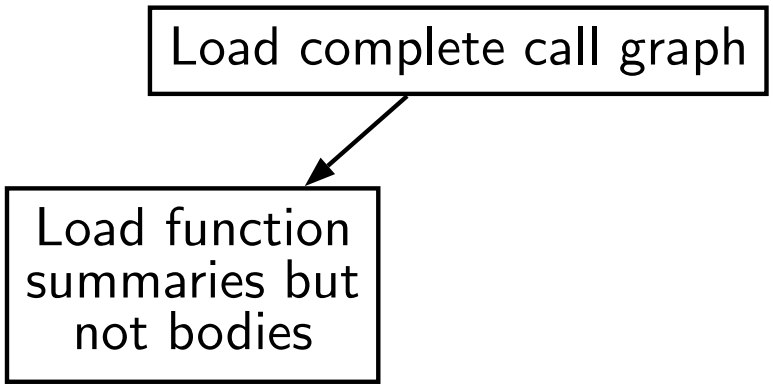
Analysis

Sequential Analysis

Transformation

Partitioned and Non-Partitioned LTO

Analysis

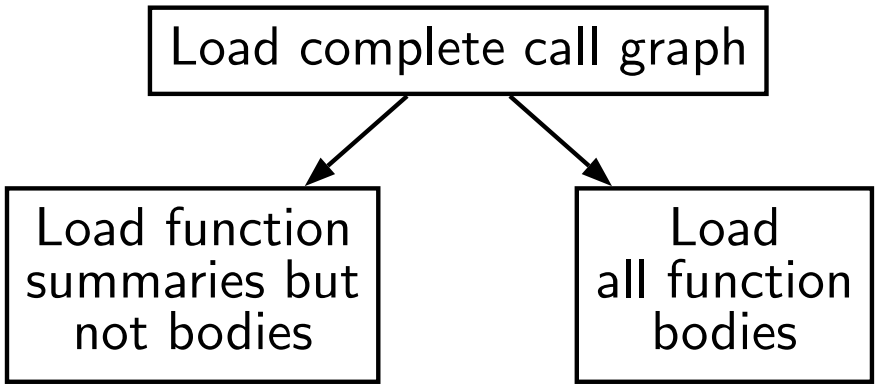


Sequential Analysis

Transformation

Partitioned and Non-Partitioned LTO

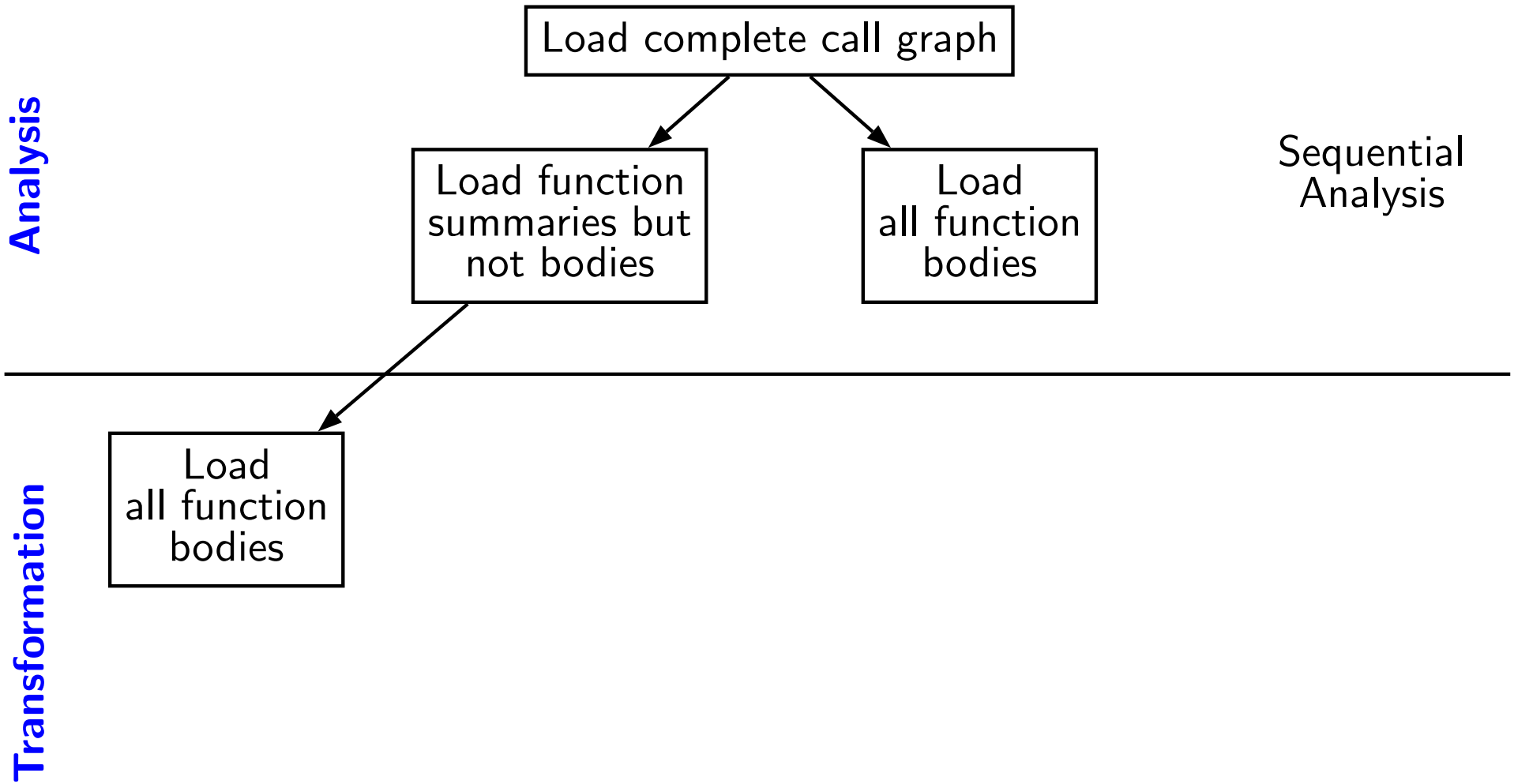
Analysis



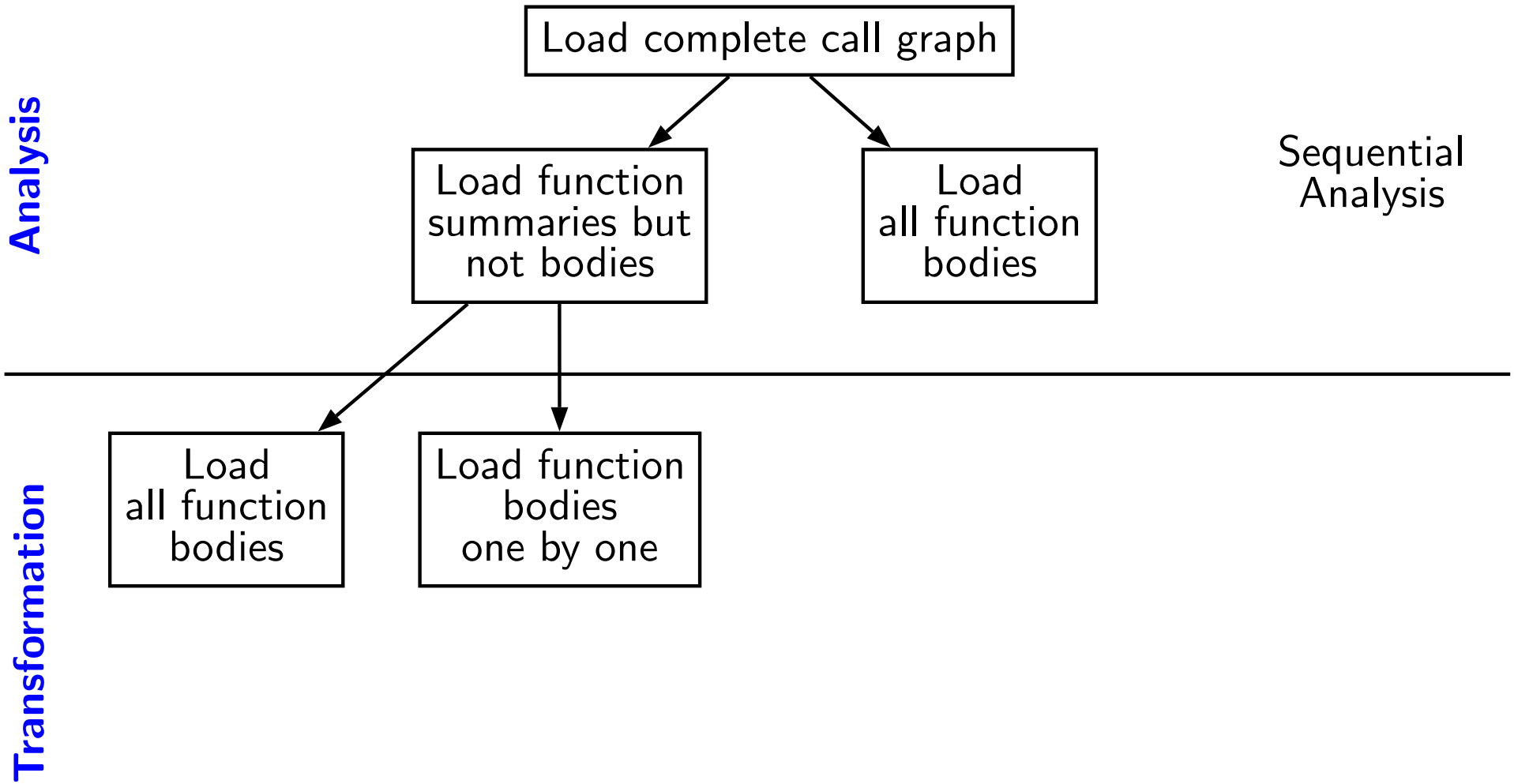
Sequential Analysis

Transformation

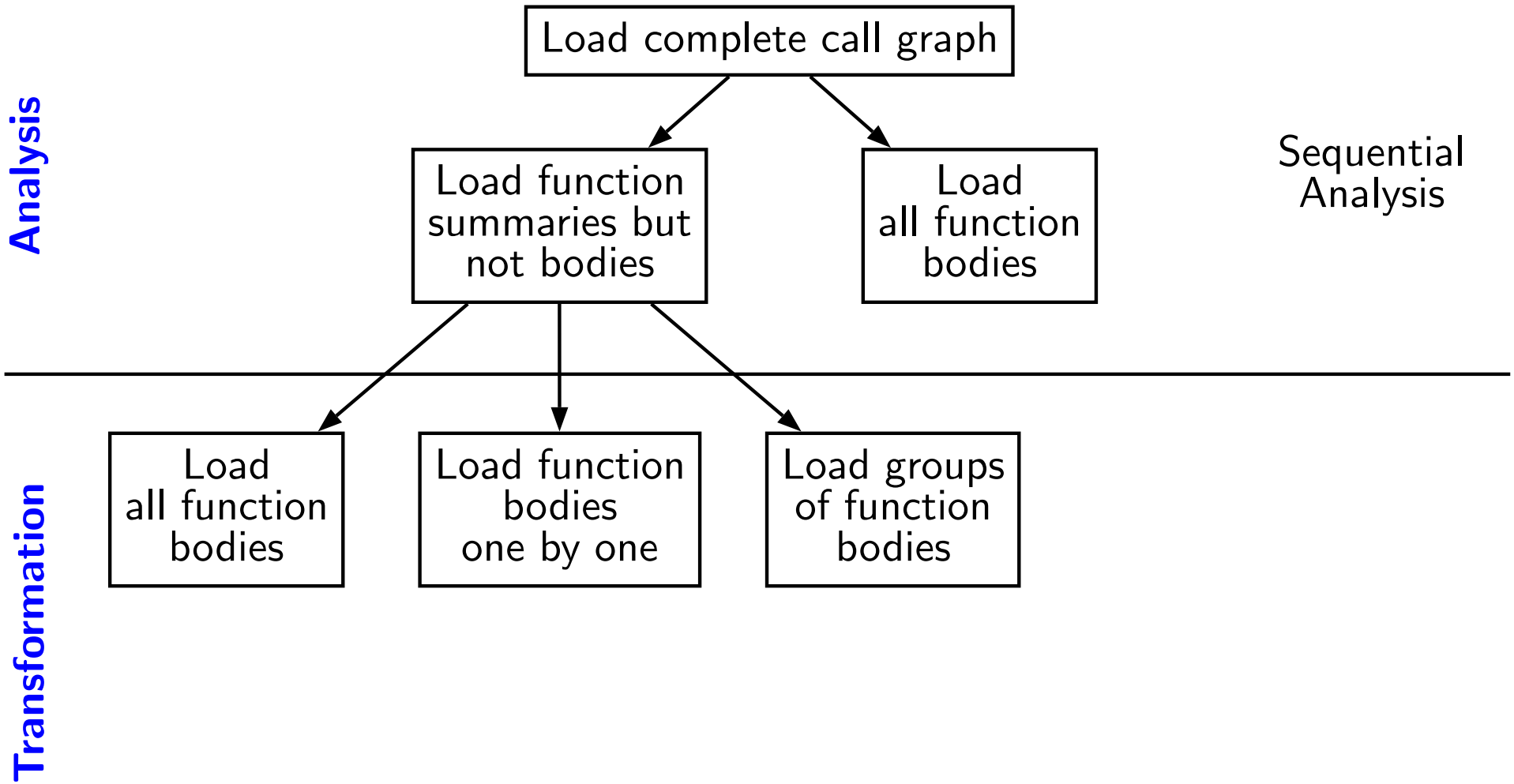
Partitioned and Non-Partitioned LTO



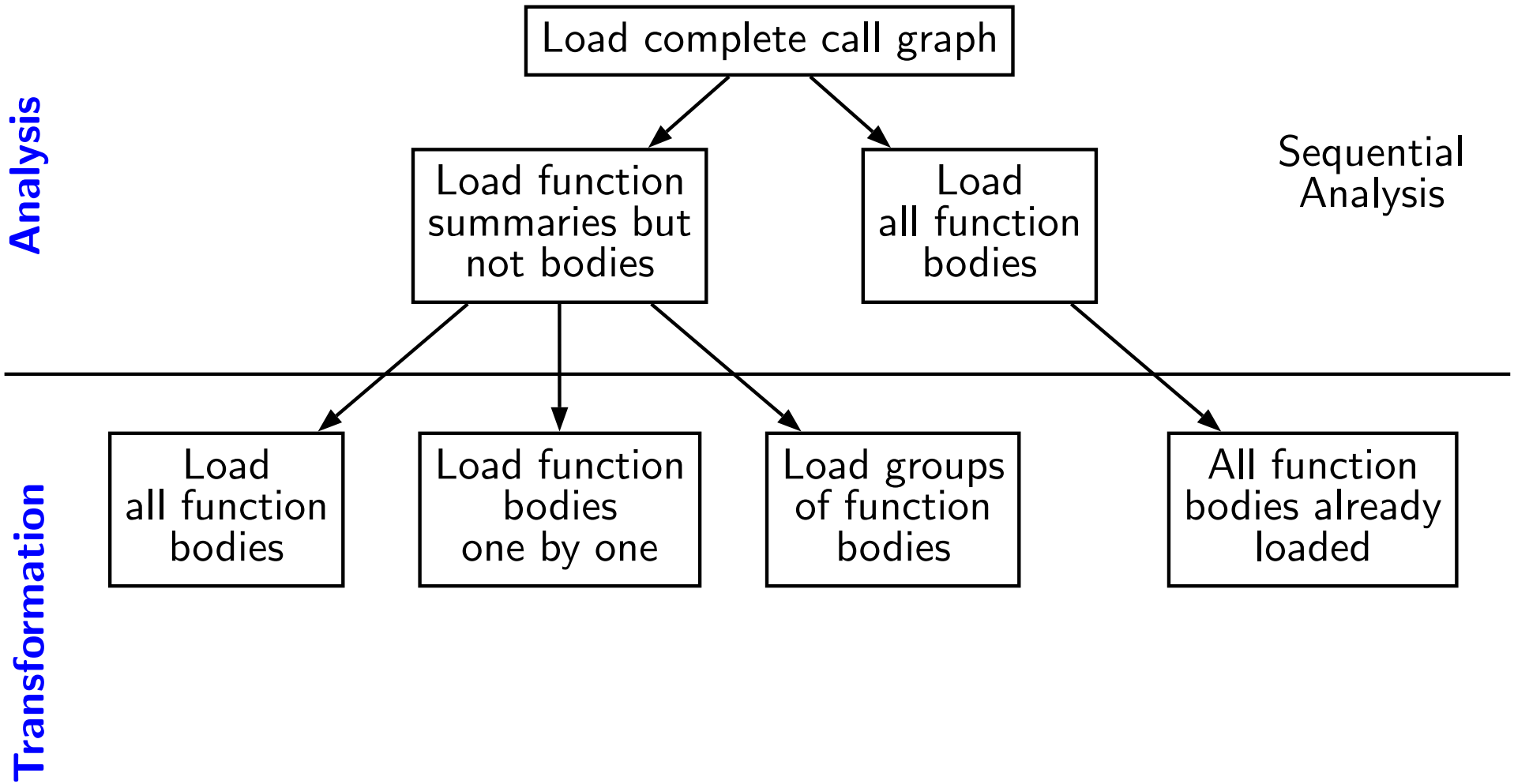
Partitioned and Non-Partitioned LTO



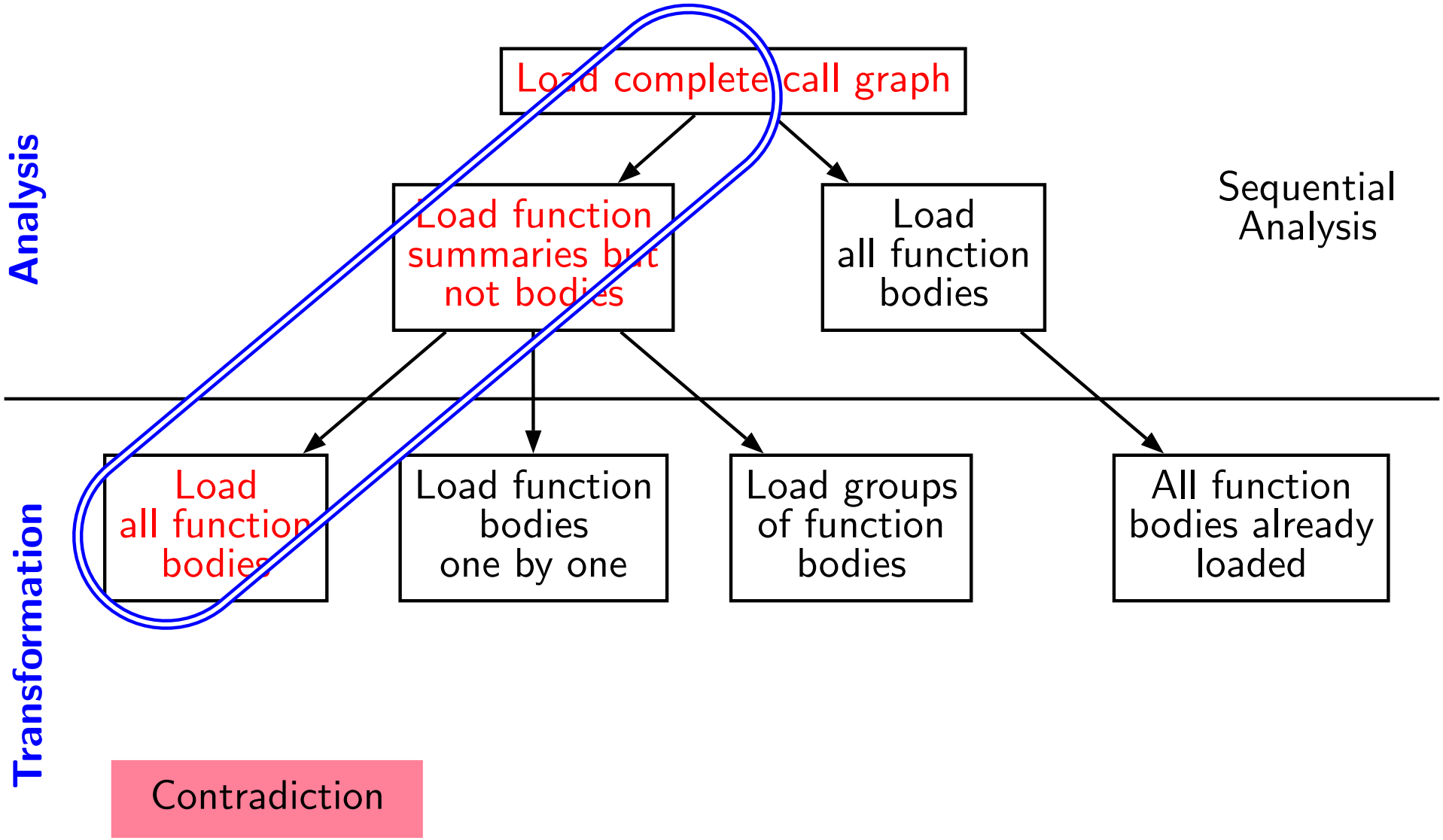
Partitioned and Non-Partitioned LTO



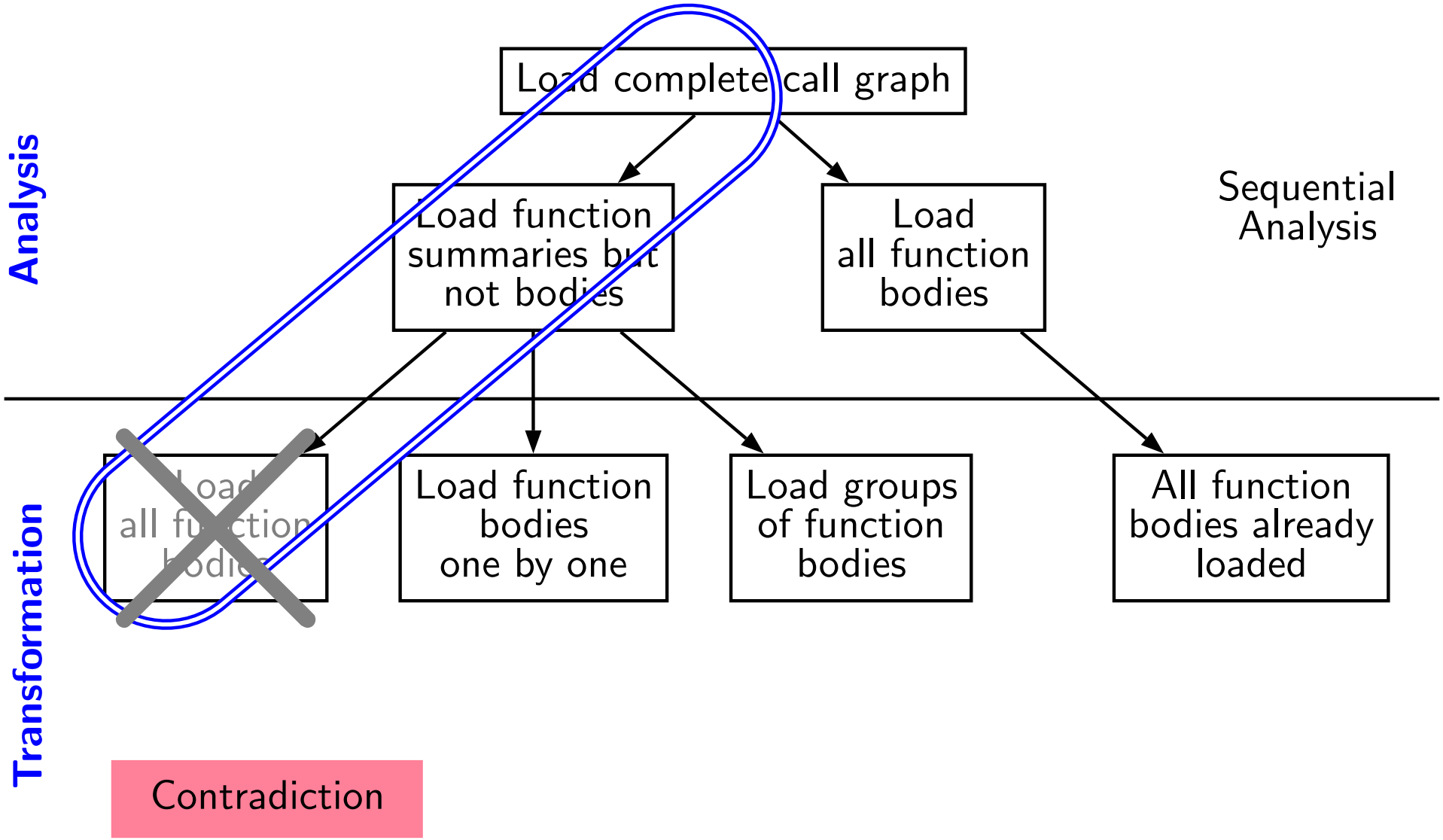
Partitioned and Non-Partitioned LTO



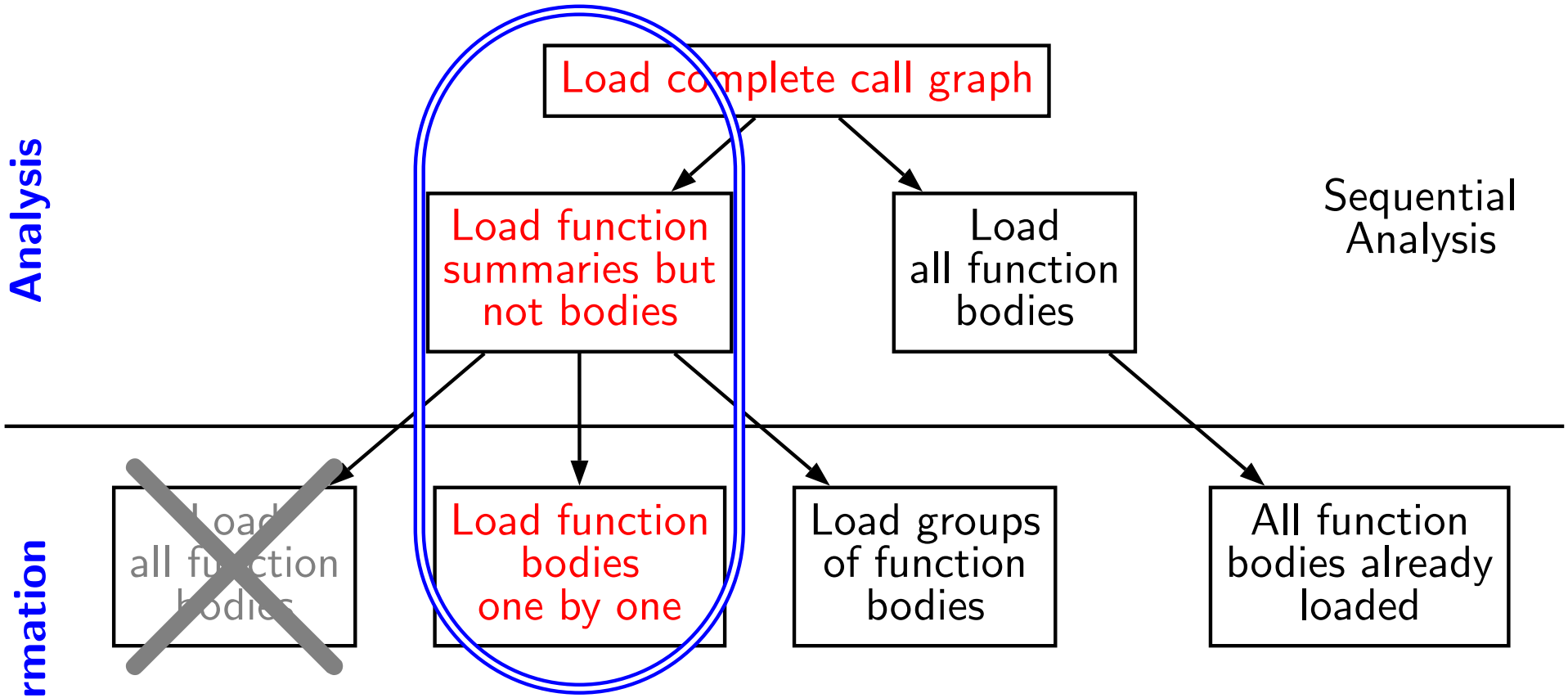
Partitioned and Non-Partitioned LTO



Partitioned and Non-Partitioned LTO

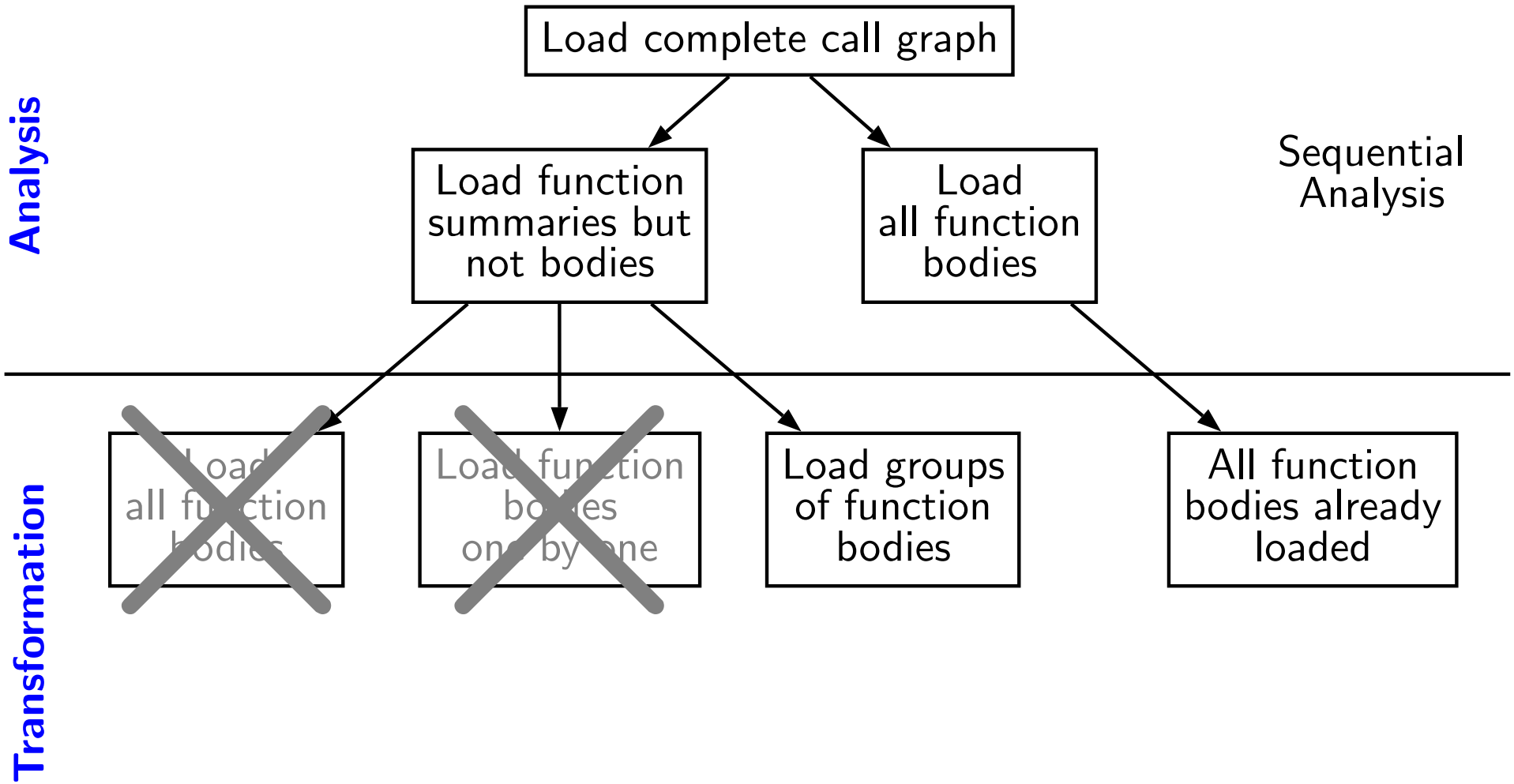


Partitioned and Non-Partitioned LTO

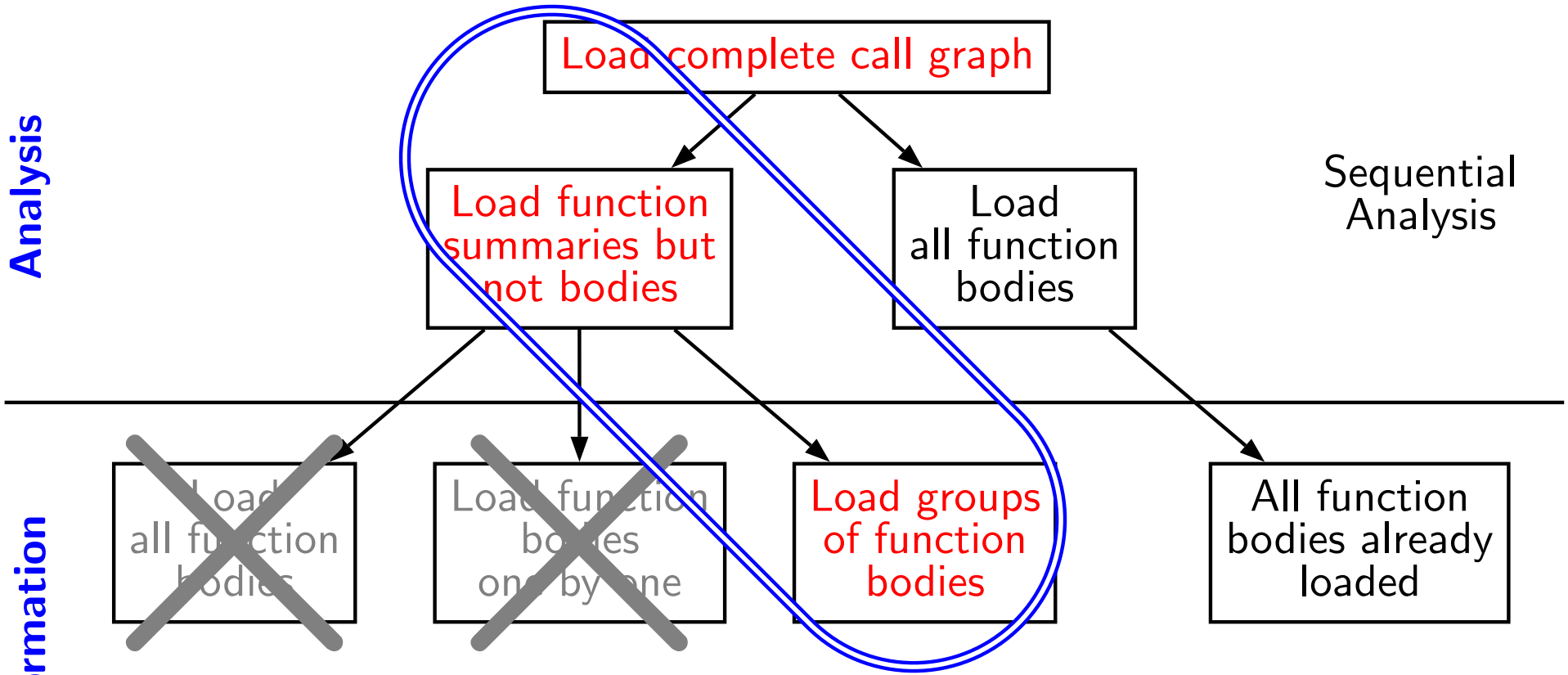


IPA not possible (only one function body at a time)
Strictly sequential transformations

Partitioned and Non-Partitioned LTO

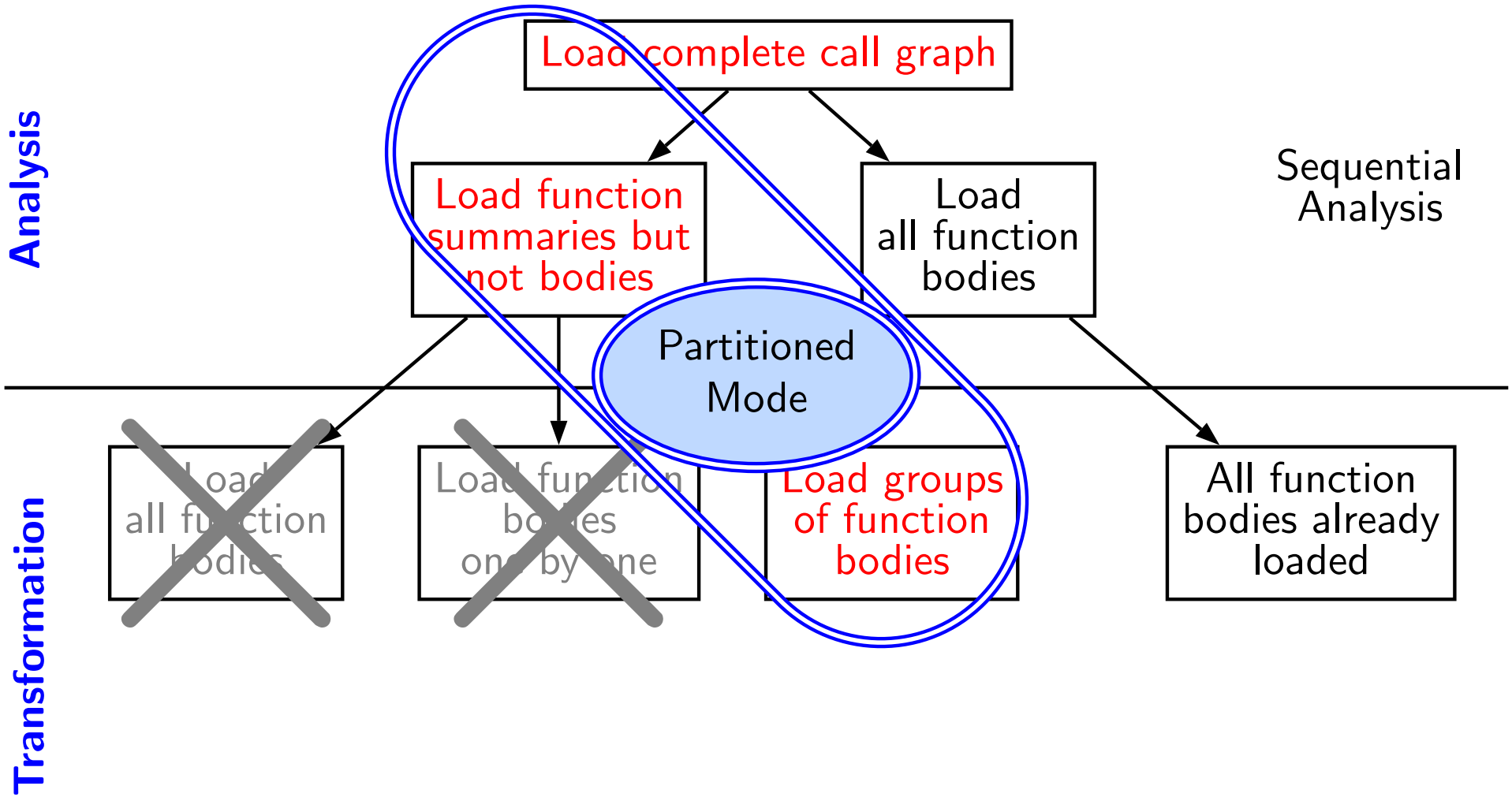


Partitioned and Non-Partitioned LTO

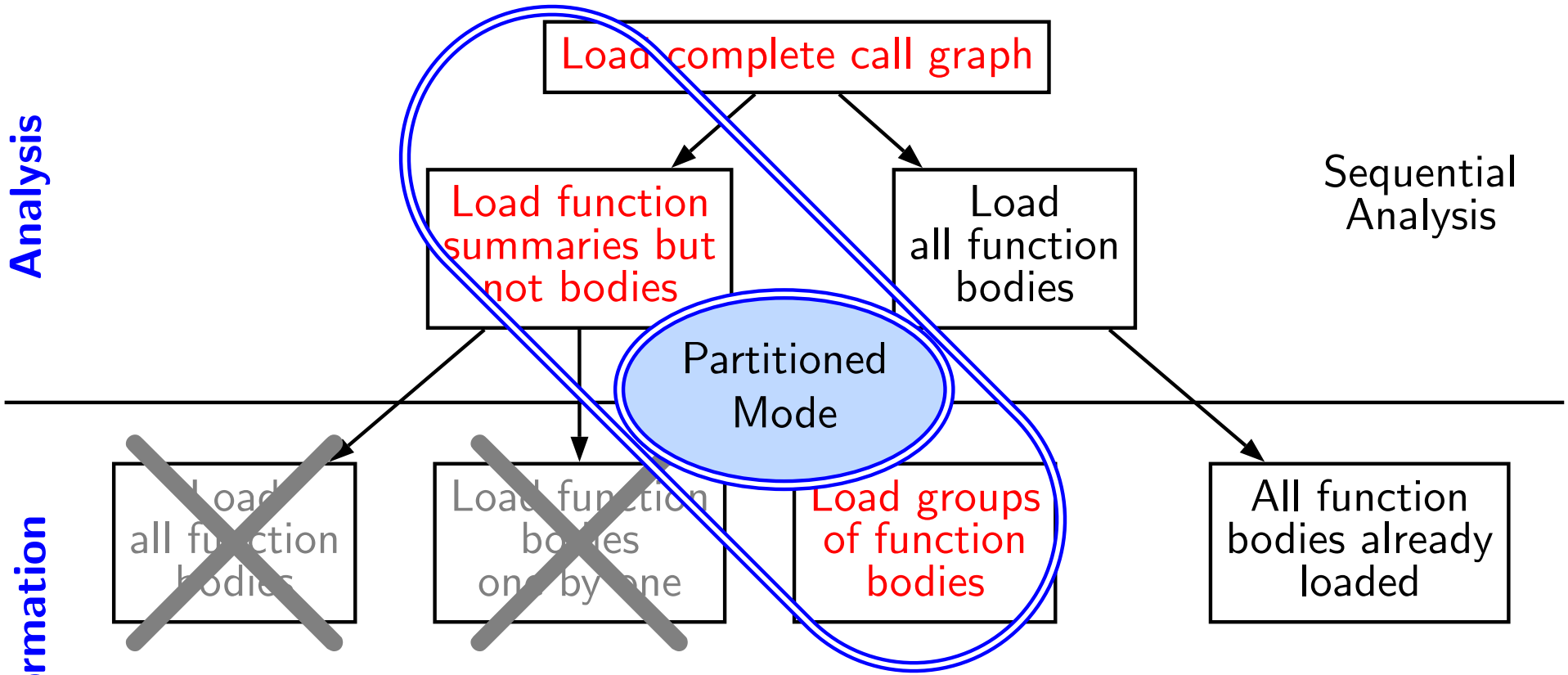


No need to load the entire program in memory
IPA possible (multiple function bodies)
Parallel transformations possible
Analysis and transformations in independent processes

Partitioned and Non-Partitioned LTO

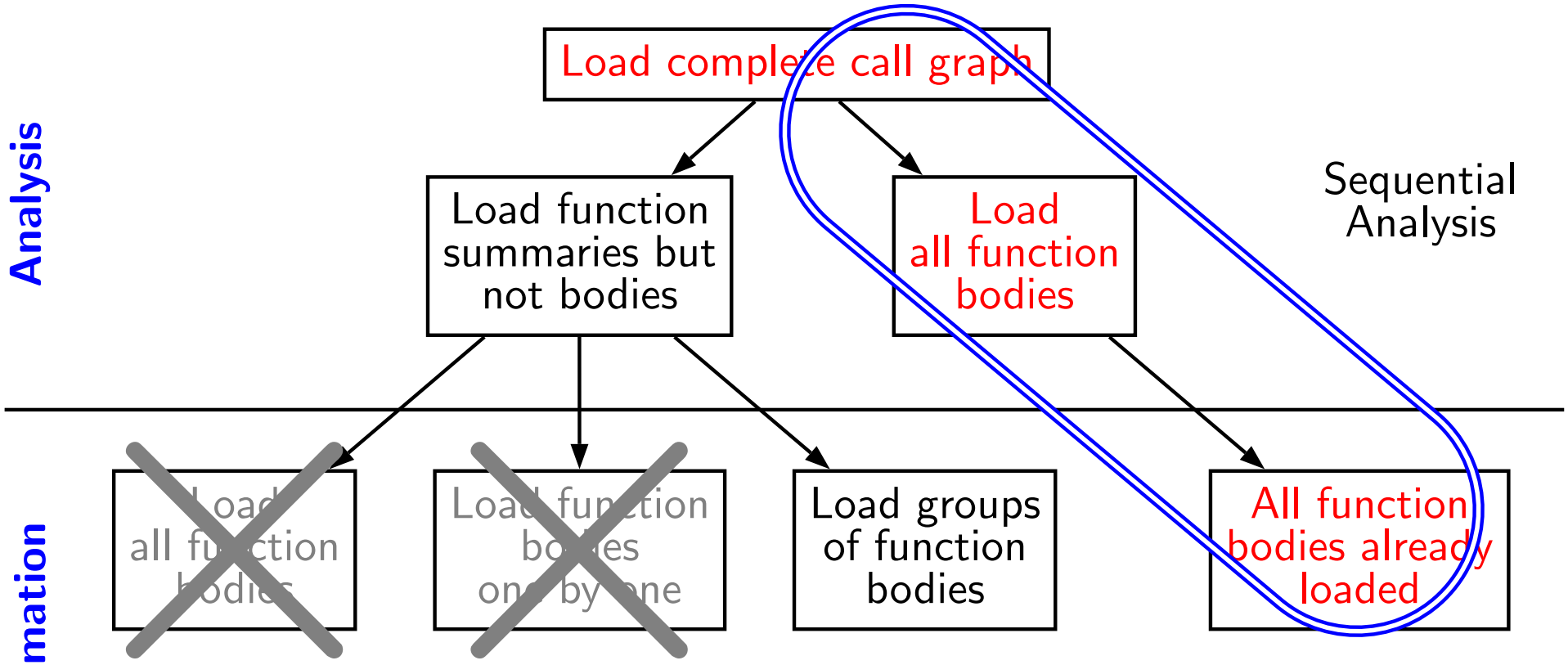


Partitioned and Non-Partitioned LTO



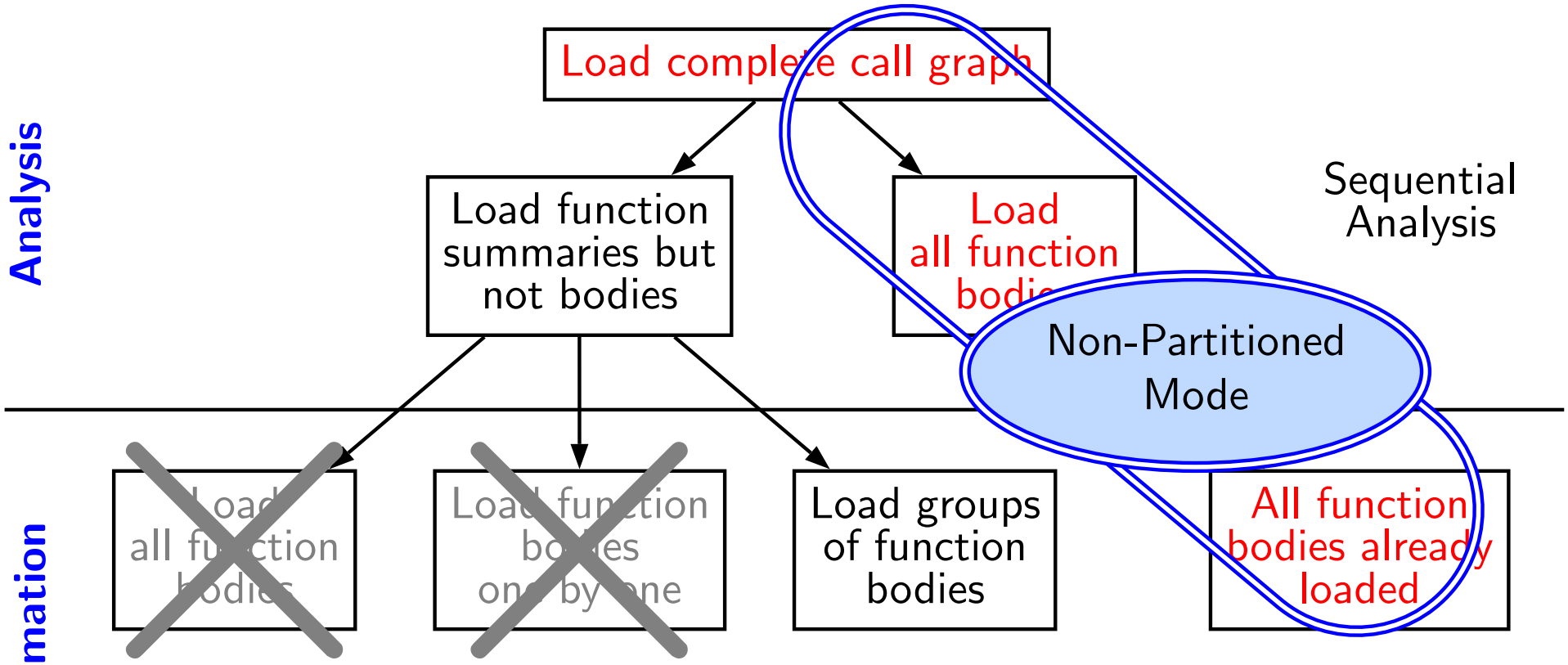
Balanced partitions `-flto -flto-partitions=balanced`
One Partition per file `-flto -flto-partitions=1to1`
Partitions by number `-flto --params lto-partitions=n`
Partitions by size `-flto --params lto-min-partition=s`

Partitioned and Non-Partitioned LTO



Entire program needs to be loaded in memory
No partitions `-flto -flto-partitions=none`
Strictly sequential transformations
Analysis and transformations in the same processes

Partitioned and Non-Partitioned LTO



Entire program needs to be loaded in memory
No partitions `-flto -flto-partitions=none`
Strictly sequential transformations
Analysis and transformations in the same processes

Partitioned LTO (aka WHOPR Mode of LTO)

- Three steps
  - LGEN:
    - generation of summary information
    - generation of translation unit information
  - WPA: Whole Program Analysis
    - Reads the call graph and not function bodies
    - Summary information for each function
  - LTRANS: Local Transformations

Partitioned LTO (aka WHOPR Mode of LTO)

- Three steps
  - LGEN: Potentially Parallel
    - generation of summary information
    - generation of translation unit information
  - WPA: Whole Program Analysis
    - Reads the call graph and not function bodies
    - Summary information for each function
  - LTRANS: Local Transformations

Partitioned LTO (aka WHOPR Mode of LTO)

- Three steps
  - LGEN: Potentially Parallel
    - generation of summary information
    - generation of translation unit information
  - WPA: Whole Program Analysis Sequential
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    - Summary information for each function
  - LTRANS: Local Transformations

Partitioned LTO (aka WHOPR Mode of LTO)

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    - generation of summary information
    - generation of translation unit information
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    - Summary information for each function
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    - generation of translation unit information
  - WPA: Whole Program Analysis Sequential
    - Reads the call graph and not function bodies
    - Summary information for each function
  - LTRANS: Local Transformations Potentially Parallel
- Processing sequence

Partitioned LTO (aka WHOPR Mode of LTO)

- Three steps
  - LGEN: Potentially Parallel
    - generation of summary information
    - generation of translation unit information
  - WPA: Whole Program Analysis Sequential
    - Reads the call graph and not function bodies
    - Summary information for each function
  - LTRANS: Local Transformations Potentially Parallel
- Processing sequence
  - `gcc` executes LGEN
  - Subsequent process of `lto1` executes WPA
  - Subsequent independent processes of `lto1` execute LTRANS

Non-Partitioned LTO

- Two steps
  - LGEN:
    - generation of translation unit information
    - no summary
  - IPA: Inter-Procedural Analysis
    - Reads the call graph and function bodies
    - Performs analysis and transformation

  IPA is a whole program analysis
  (processes the entire program together)

Non-Partitioned LTO

- Two steps
  - LGEN: Potentially Parallel
    - generation of translation unit information
    - no summary
  - IPA: Inter-Procedural Analysis
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    - Performs analysis and transformation

  IPA is a whole program analysis
  (processes the entire program together)

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  IPA is a whole program analysis
  (processes the entire program together)

Non-Partitioned LTO

- Two steps
  - LGEN: Potentially Parallel
    - generation of translation unit information
    - no summary
  - IPA: Inter-Procedural Analysis Sequential
    - Reads the call graph and function bodies
    - Performs analysis and transformation

    IPA is a whole program analysis
    (processes the entire program together)

- Processing sequence

Non-Partitioned LTO

- Two steps
  - LGEN: Potentially Parallel
    - generation of translation unit information
    - no summary
  - IPA: Inter-Procedural Analysis Sequential
    - Reads the call graph and function bodies
    - Performs analysis and transformation

    IPA is a whole program analysis
    (processes the entire program together)

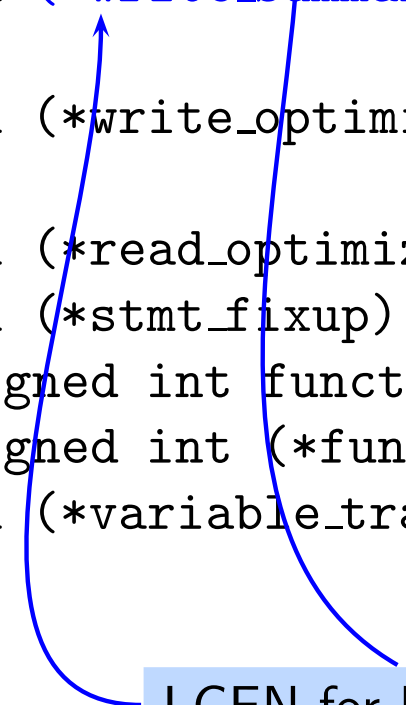
- Processing sequence
  - `gcc` executes LGEN
  - Subsequent process of `lto1` executes IPA

LTO Pass Hooks

```
struct ipa_opt_pass_d
{
  struct opt_pass pass;
  void (*generate_summary) (void);
  void (*read_summary) (void);
  void (*write_summary) (struct cgraph_node_set_def *,
                         struct varpool_node_set_def *);
  void (*write_optimization_summary)(struct cgraph_node_set_def *,
                                     struct varpool_node_set_def *);
  void (*read_optimization_summary) (void);
  void (*stmt_fixup) (struct cgraph_node *, gimple *);
  unsigned int function_transform_todo_flags_start;
  unsigned int (*function_transform) (struct cgraph_node *);
  void (*variable_transform) (struct varpool_node *);
};
```

LTO Pass Hooks

```
struct ipa_opt_pass_d
{
  struct opt_pass pass;
  void (*generate_summary) (void);
  void (*read_summary) (void);
  void (*write_summary) (struct cgraph_node_set_def *,
                         struct varpool_node_set_def *);
  void (*write_optimization_summary)(struct cgraph_node_set_def *,
                                     struct varpool_node_set_def *);
  void (*read_optimization_summary) (void);
  void (*stmt_fixup) (struct cgraph_node *, gimple *);
  unsigned int function_transform_todo_flags_start;
  unsigned int (*function_transform) (struct cgraph_node *);
  void (*variable_transform) (struct varpool_node *);
};
```



LGEN for Partitioned LTO

LTO Pass Hooks

```
struct ipa_opt_pass_d
{
  struct opt_pass pass;
  void (*generate_summary) (void);
  void (*read_summary) (void);
  void (*write_summary) (struct cgraph_node_set_def *,
                         struct varpool_node_set_def *);
  void (*write_optimization_summary)(struct cgraph_node_set_def *,
                                     struct varpool_node_set_def *);
  void (*read_optimization_summary) (void);
  void (*stmt_fixup) (struct cgraph_node *, gimple *);
  unsigned int function_transform_todo_flags_start;
  unsigned int (*function_transform) (struct cgraph_node *);
  void (*variable_transform) (struct varpool_node *);
};
```

LGEN for Non-Partitioned LTO

LTO Pass Hooks

```
struct ipa_opt_pass_d
{
  struct opt_pass pass; (member  void (*execute) (void);)
  void (*generate_summary) (void);
  void (*read_summary) (void);
  void (*write_summary) (struct cgraph_node_set_def *,
                         struct varpool_node_set_def *);
  void (*write_optimization_summary)(struct cgraph_node_set_def *,
                                     struct varpool_node_set_def *);
  void (*read_optimization_summary) (void);
  void (*stmt_fixup) (struct cgraph_node *, gimple *);
  unsigned int function_transform_todo_flags_start;
  unsigned int (*function_transform) (struct cgraph_node *);
  void (*variable_transform) (struct varpool_node *);
};
```

WPA for Partitioned LTO

LTO Pass Hooks

```
struct ipa_opt_pass_d
{
  struct opt_pass pass; (member  void (*execute) (void);)
  void (*generate_summary) (void);
  void (*read_summary) (void);
  void (*write_summary) (struct cgraph_node_set_def *,
                         struct varpool_node_set_def *);
  void (*write_optimization_summary)(struct cgraph_node_set_def *,
                                     struct varpool_node_set_def *);
  void (*read_optimization_summary) (void);
  void (*stmt_fixup) (struct cgraph_node *, gimple *);
  unsigned int function_transform_todo_flags_start;
  unsigned int (*function_transform) (struct cgraph_node *);
  void (*variable_transform) (struct varpool_node *);
};
```

IPA for Non-Partitioned LTO

LTO Pass Hooks

```
struct ipa_opt_pass_d
{
  struct opt_pass pass;
  void (*generate_summary) (void);
  void (*read_summary) (void);
  void (*write_summary) (struct cgraph_node_set_def *,
                         struct varpool_node_set_def *);
  void (*write_optimization_summary)(struct cgraph_node_set_def *,
                                     struct varpool_node_set_def *);
  void (*read_optimization_summary) (void);
  void (*stmt_fixup) (struct cgraph_node *, gimple *);
  unsigned int function_transform_todo_flags_start;
  unsigned int (*function_transform) (struct cgraph_node *);
  void (*variable_transform) (struct varpool_node *);
};
```

LTRANS for Partitioned LTO

lto1 Control Flow

```
lto_main
   lto_init
      lto_process_name
      lto_reader_init
   read_cgraph_and_symbols
   if (flag_wpa)
      /* WPA for partitioned LTO */
      do_whole_program_analysis
         materialize_cgraph
         execute_ipa_pass_list (all_regular_ipa_passes)
         lto_wpa_write_files
   else
      /* IPA for non-partitioned LTO */
      /* Only LTRANS for partitioned LTO */
      materialize_cgraph
      cgraph_optimize
```

cc1 Control Flow: A Recap

```
toplev_main   /* In file toplev.c */
  compile_file
    lang_hooks.parse_file=>c_common_parse_file
    lang_hooks.decls.final_write_globals=>c_write_global_declarations
      cgraph_finalize_compilation_unit
        cgraph_analyze_functions     /* Create GIMPLE */
          cgraph_analyze_function       /* Create GIMPLE */
              ...
          cgraph_optimize
            ipa_passes
              execute_ipa_pass_list(all_small_ipa_passes) /*!in lto*/
              execute_ipa_summary_passes(all_regular_ipa_passes)
              execute_ipa_summary_passes(all_lto_gen_passes)
              ipa_write_summaries
            execute_ipa_pass_list(all_late_ipa_passes)
            cgraph_expand_all_functions
              cgraph_expand_function
              /* Intra. GIMPLE, expansion, and RTL passes */
```


cc1 and Non-Partitioned lto1

```
toplev_main
...
  compile_file
  ...
    cgraph_analyze_function
```

cc1

```
cgraph_optimize
...
  ipa_passes
  ...
  cgraph_expand_all_functions
    ...
    tree_rest_of_compilation
```

cc1 and Non-Partitioned lto1

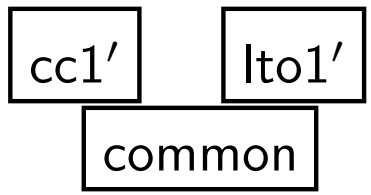
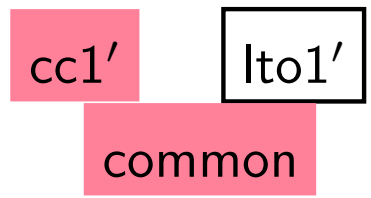
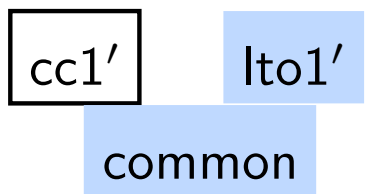
```
toplev_main
...
  compile_file
  ...
    cgraph_analyze_function
```

```
lto_main
...
  read_cgraph_and_symbols
  ...
    materialize_cgraph
```

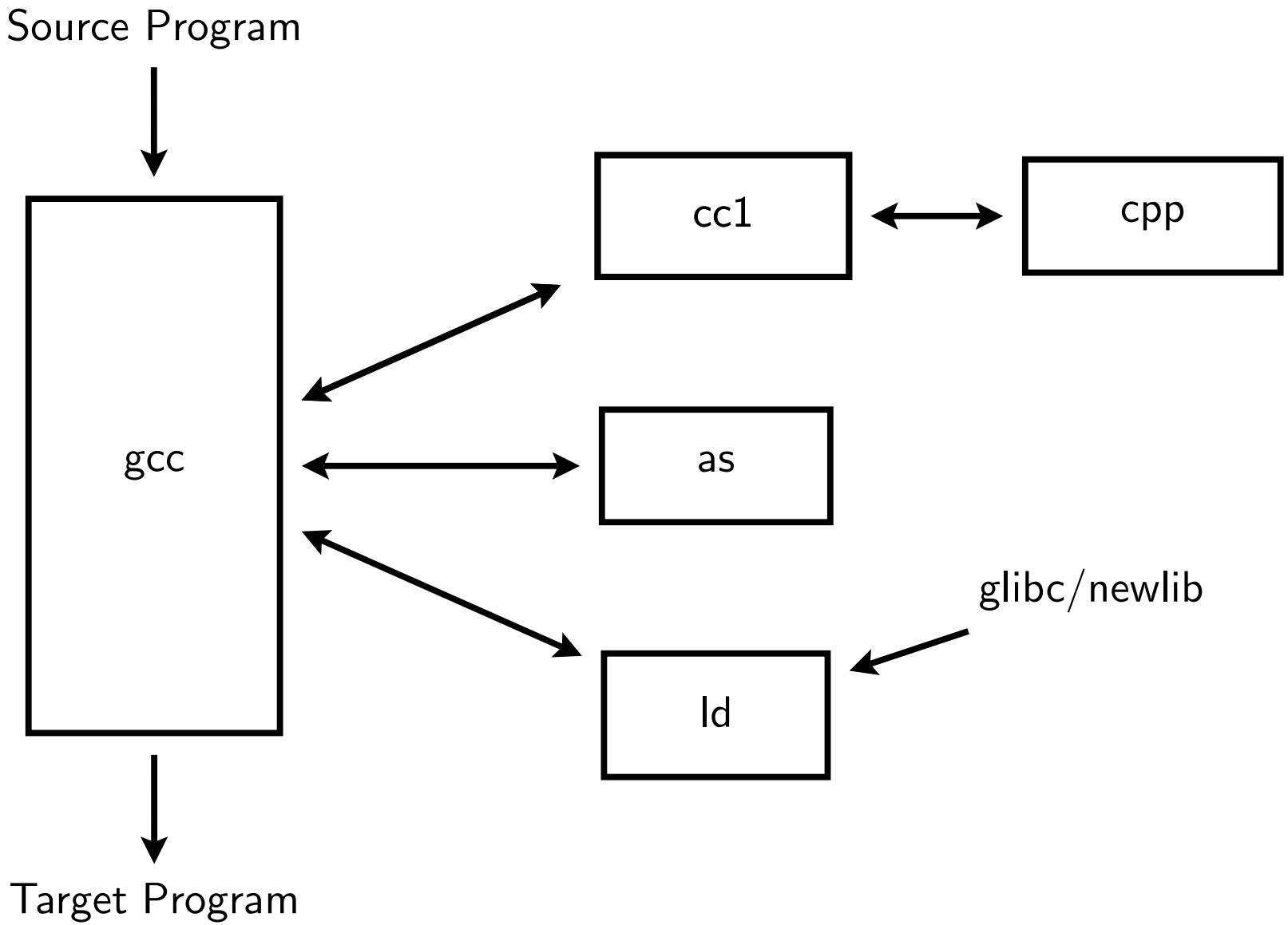
```
cgraph_optimize
...
  ipa_passes
  ...
  cgraph_expand_all_functions
    ...
    tree_rest_of_compilation
```

lto1

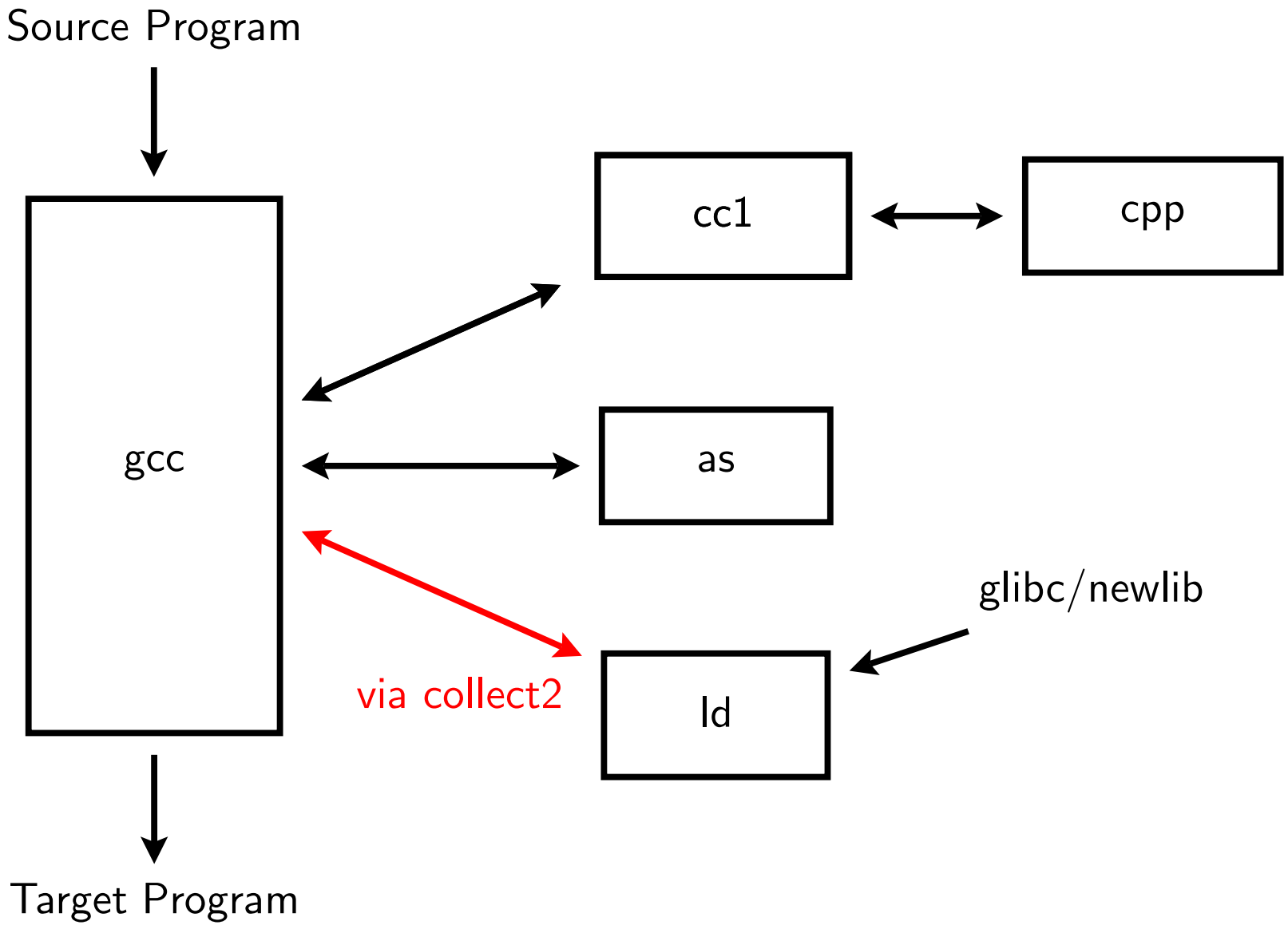
Our Pictorial Convention

Source code	
cc1 executable	
lto1 executable	

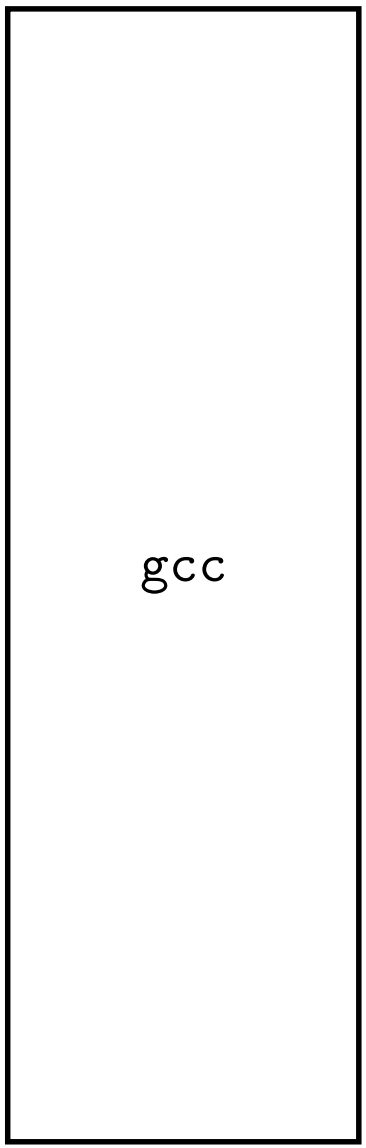
The GNU Tool Chain: Our First Picture



The GNU Tool Chain: Our First Picture



The GNU Tool Chain for Non-Partitioned LTO Support



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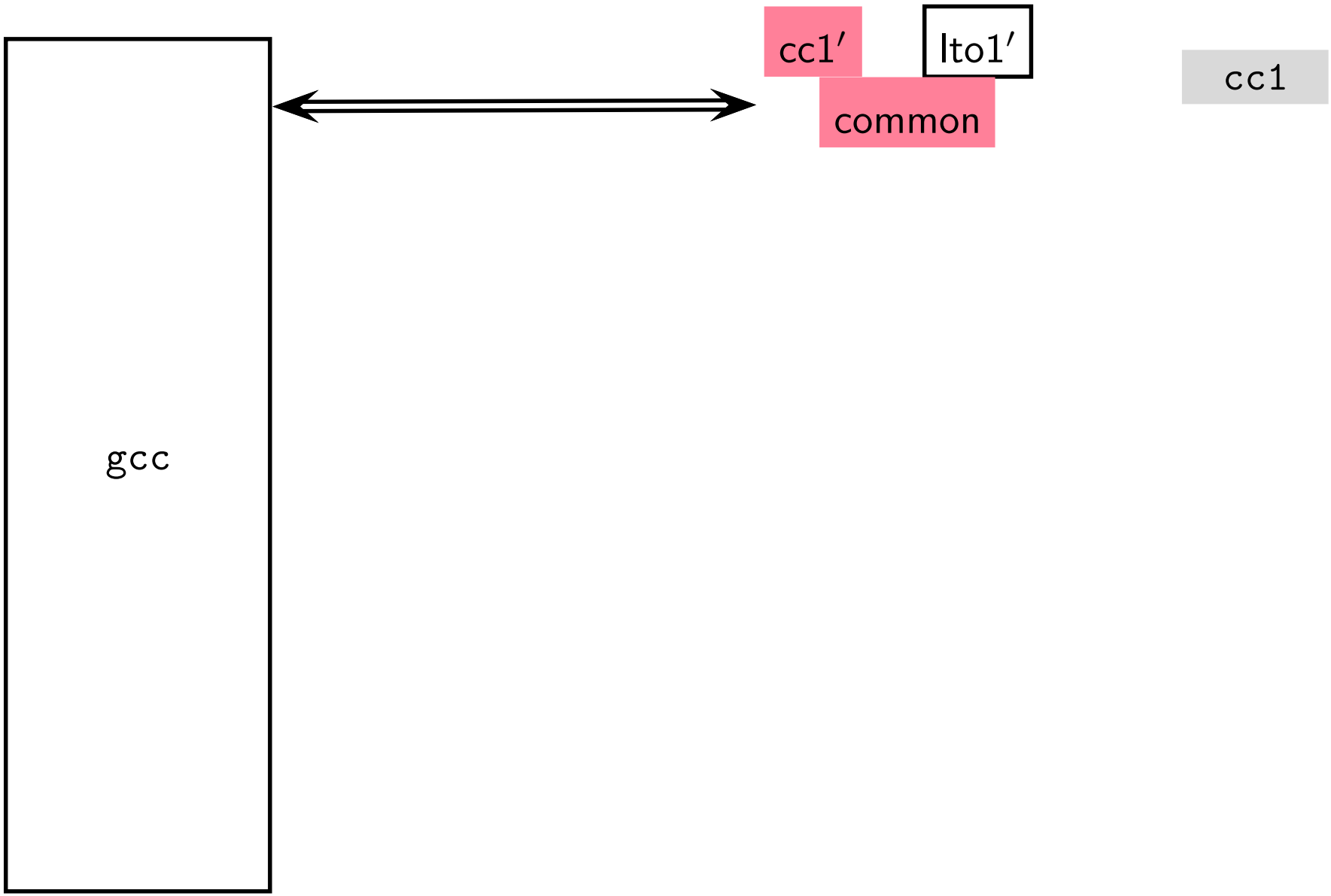

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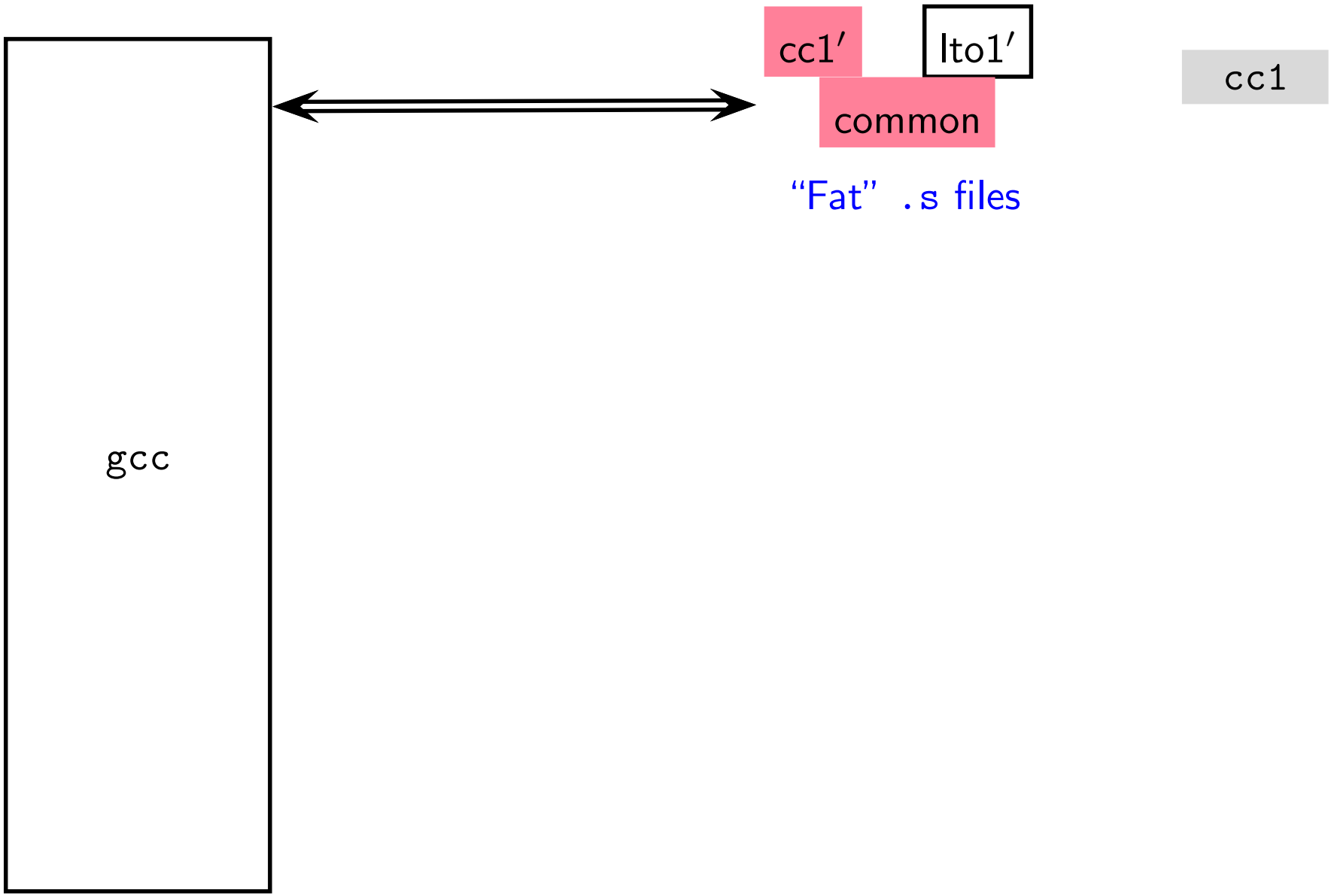
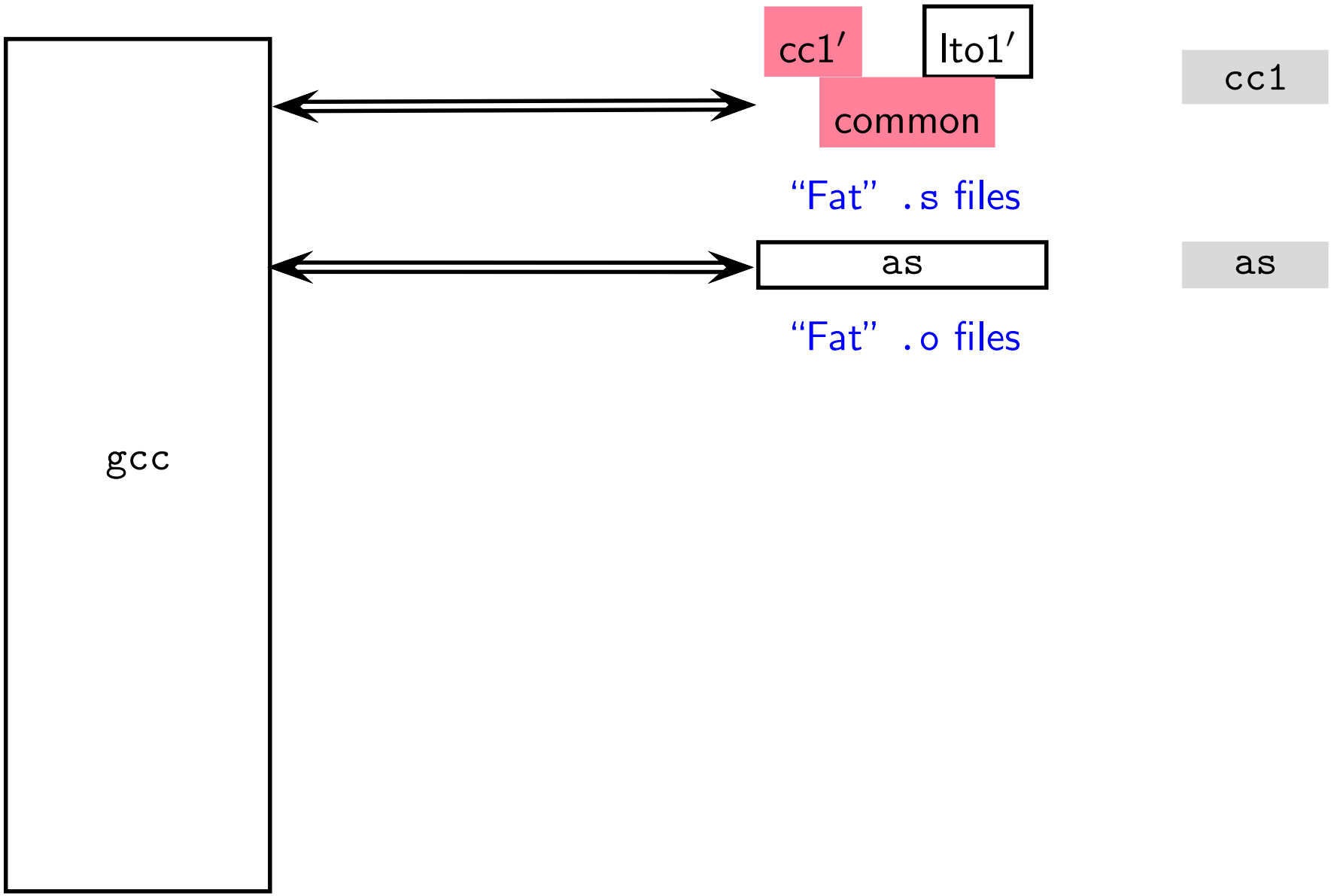


The GNU Tool Chain for Non-Partitioned LTO Support



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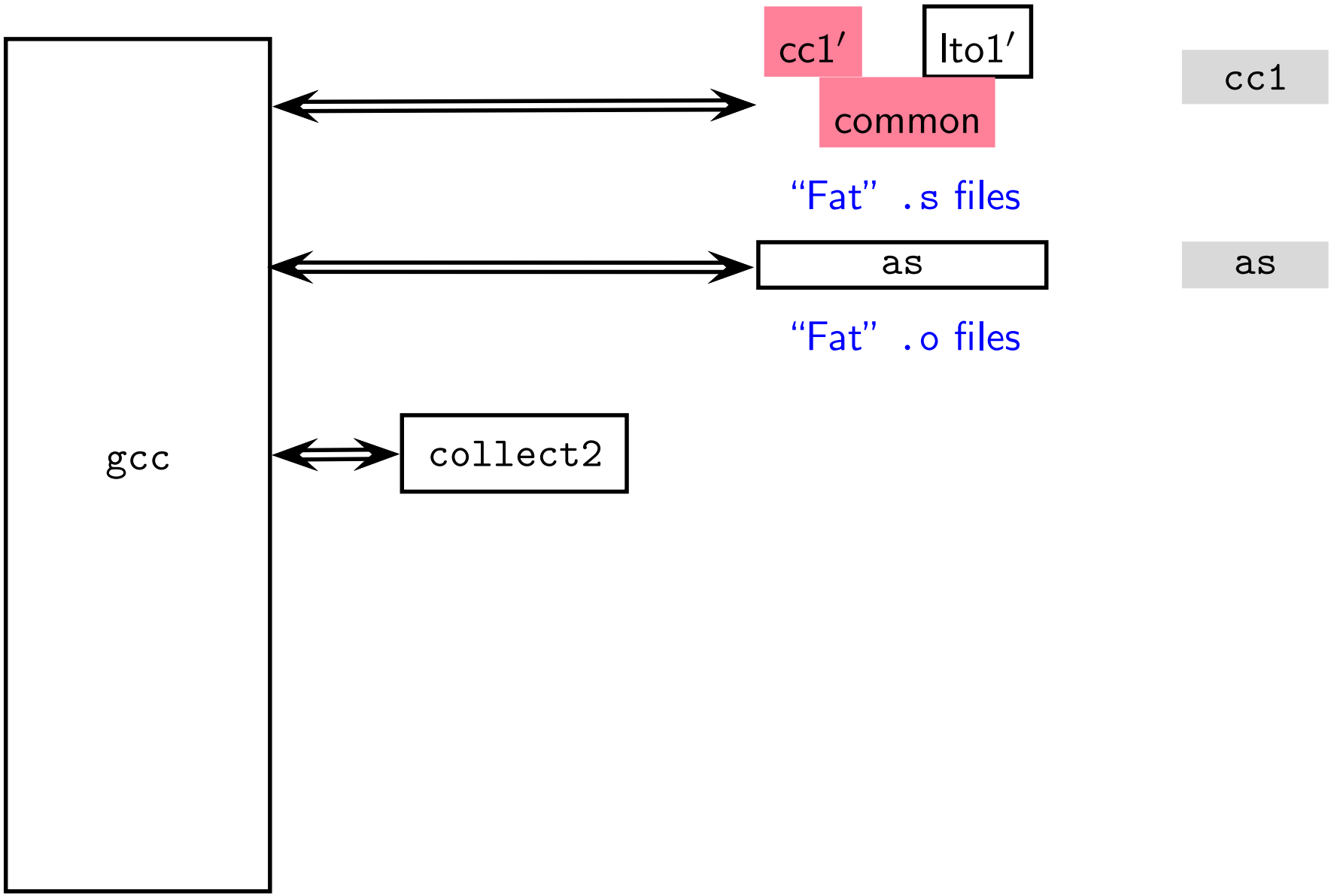
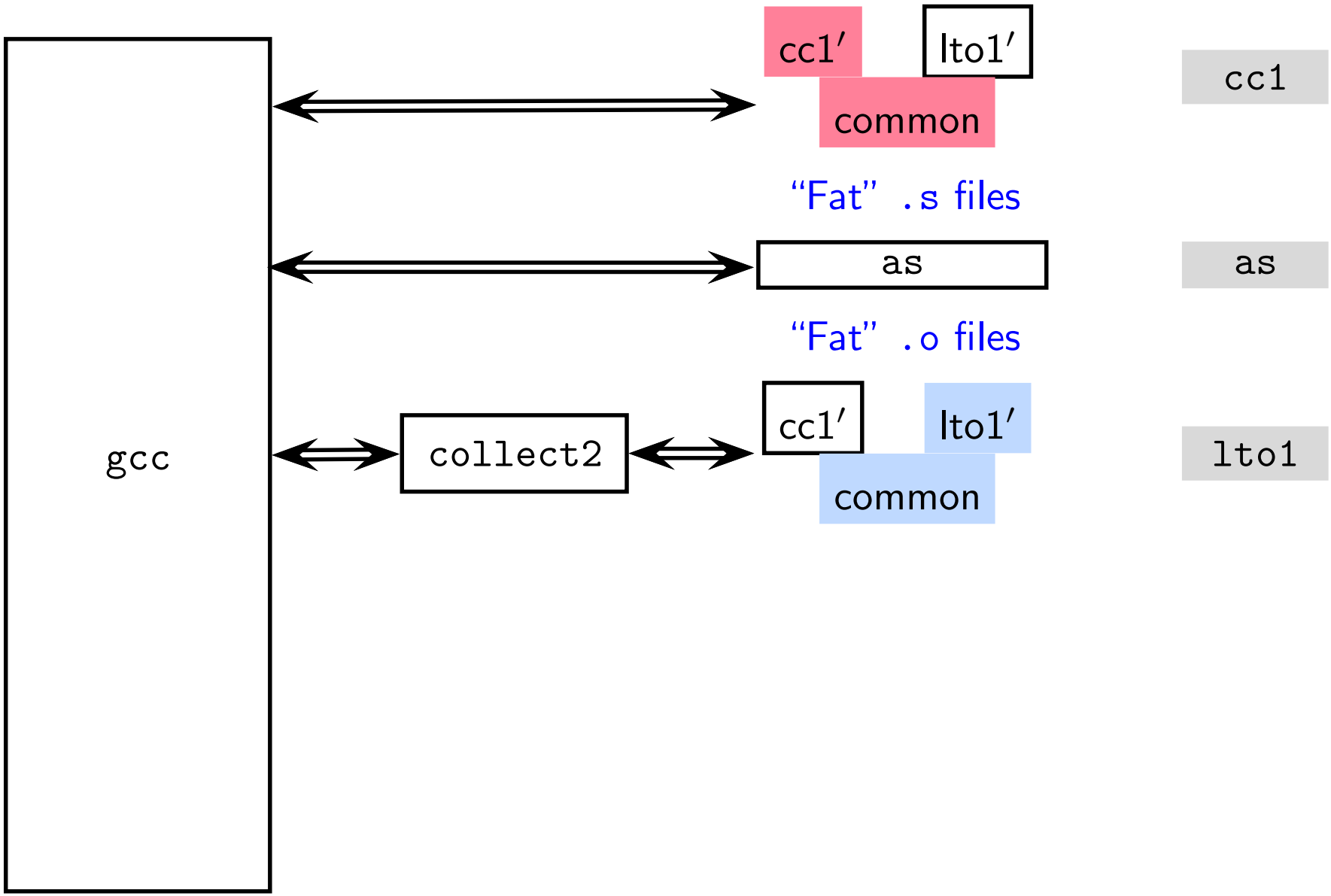
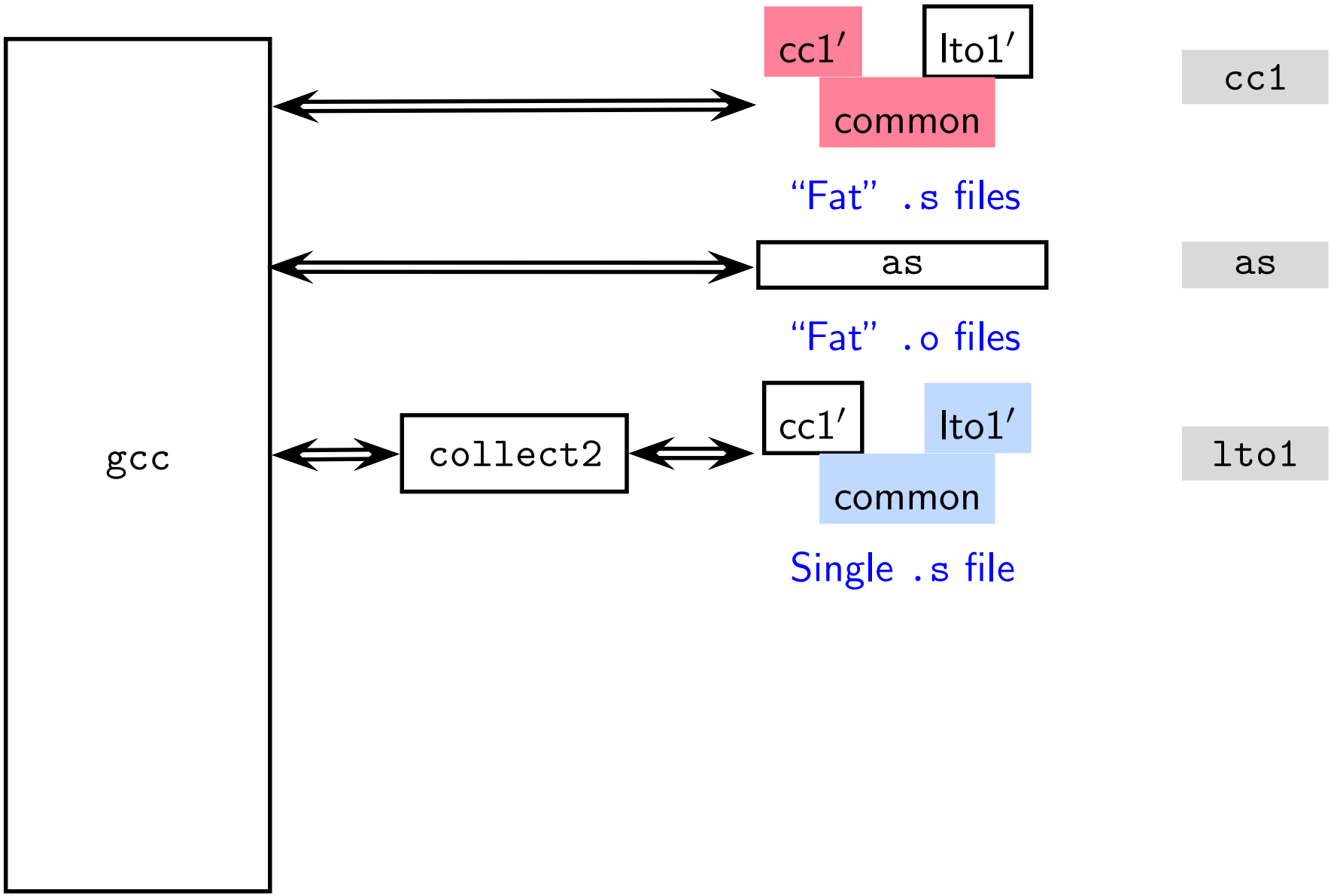


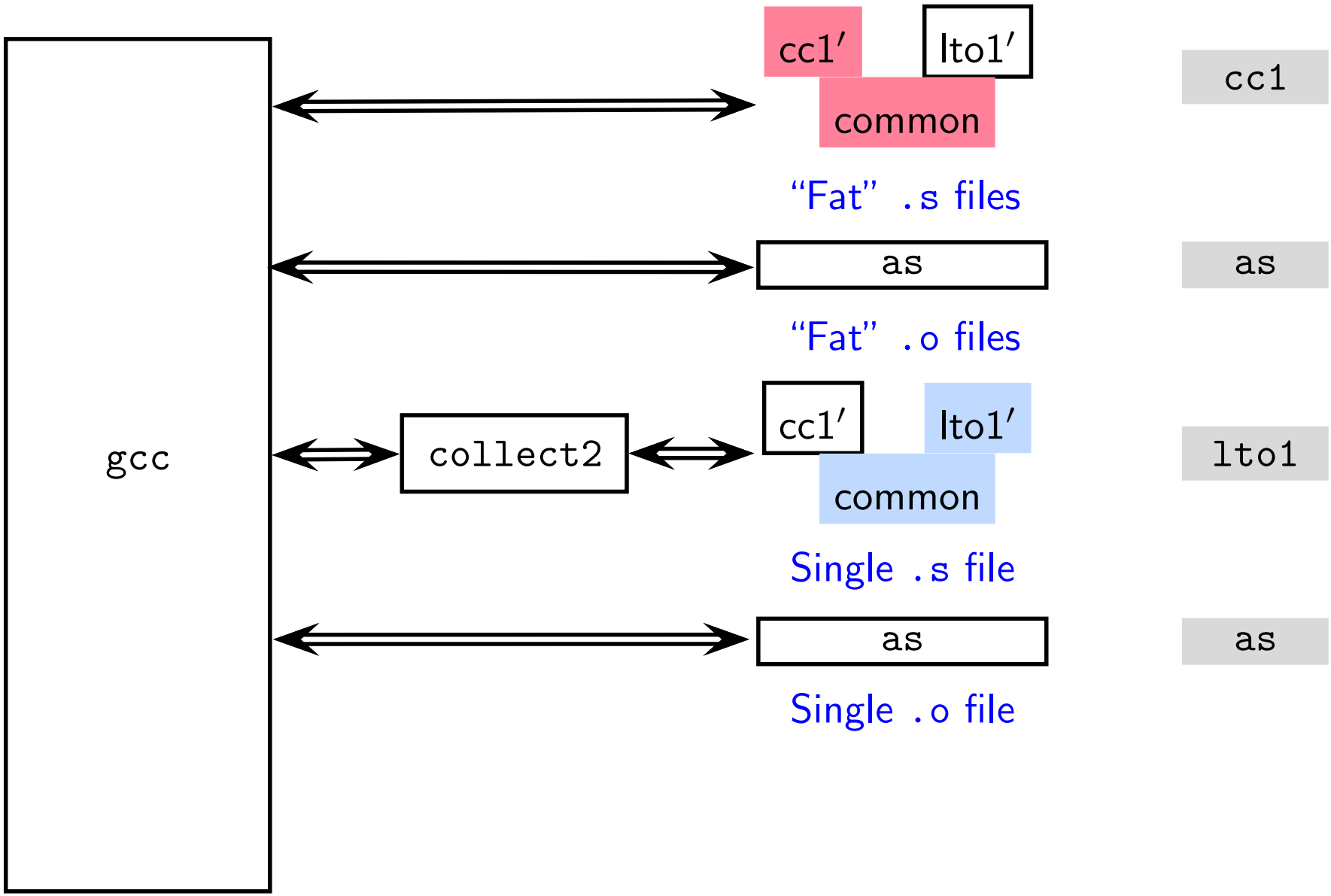
The GNU Tool Chain for Non-Partitioned LTO Support



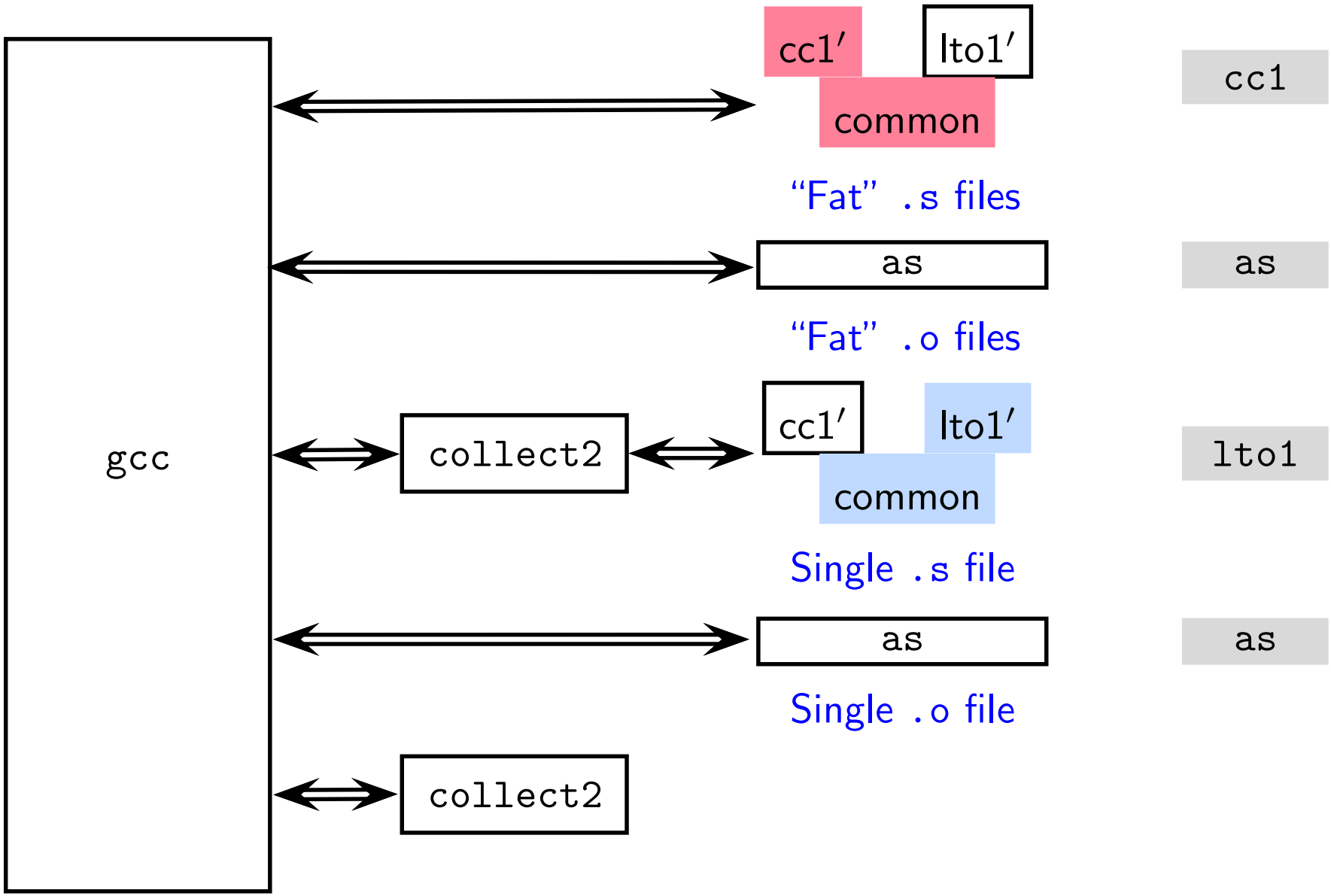
The GNU Tool Chain for Non-Partitioned LTO Support



The GNU Tool Chain for Non-Partitioned LTO Support



The GNU Tool Chain for Non-Partitioned LTO Support



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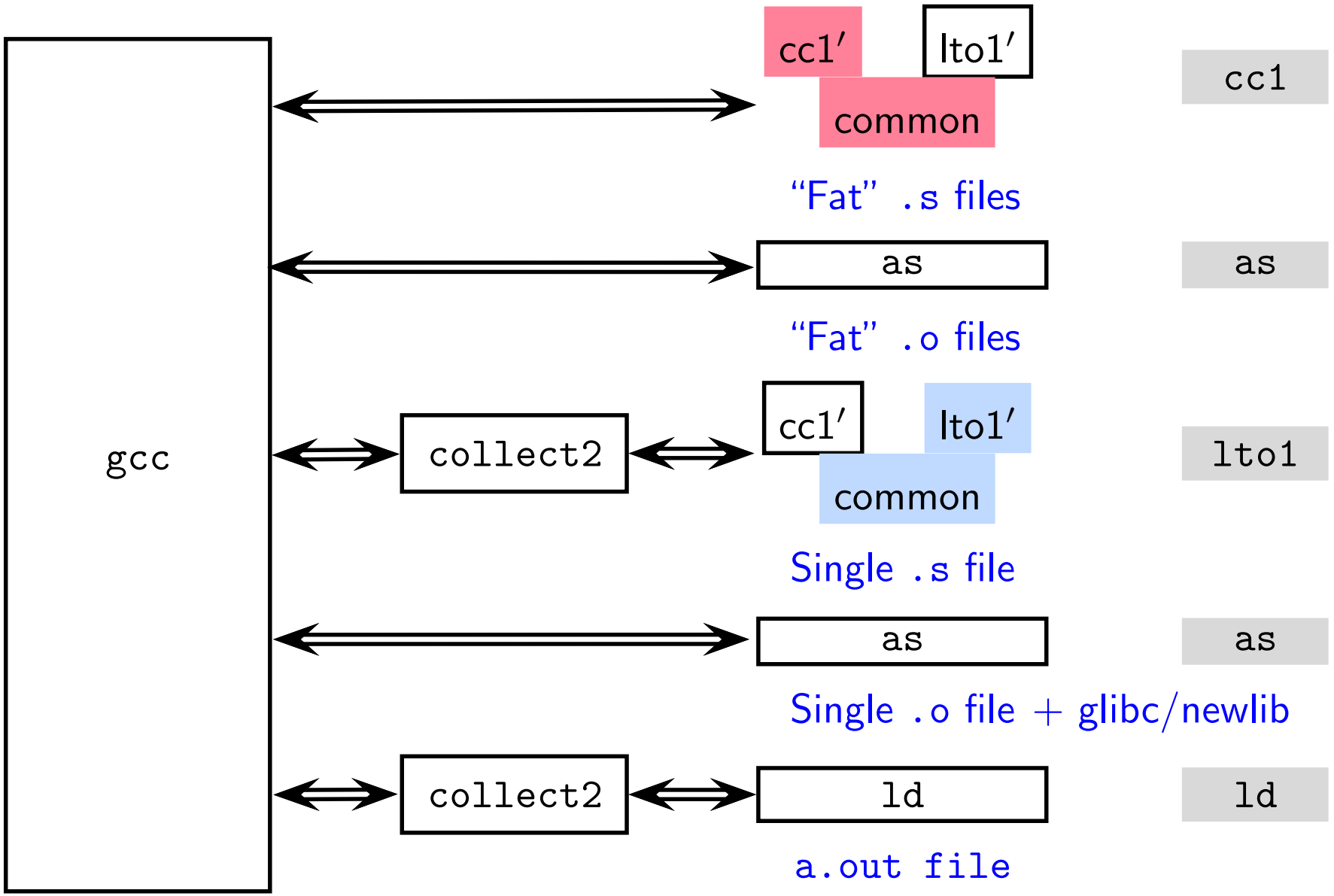
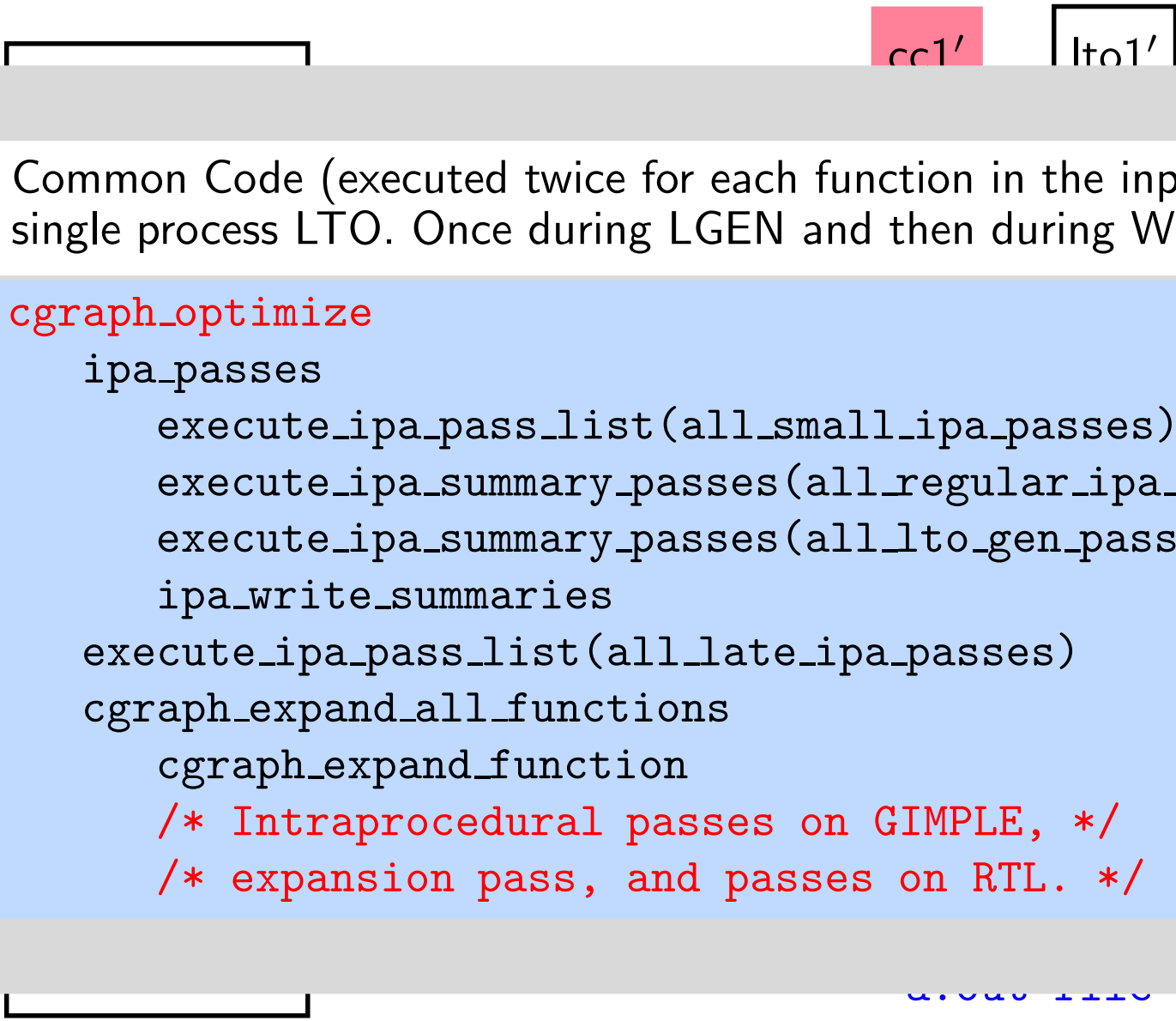


The GNU Tool Chain for Non-Partitioned LTO Support

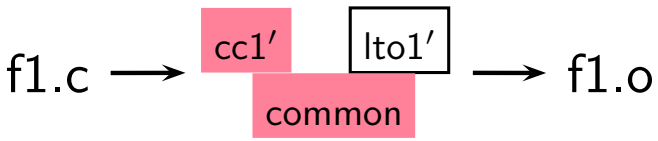


Common Code (executed twice for each function in the input program for single process LTO. Once during LGEN and then during WPA + LTRANS)

```
cgraph_optimize
   ipa_passes
      execute_ipa_pass_list(all_small_ipa_passes)/*!in lto*/
      execute_ipa_summary_passes(all_regular_ipa_passes)
      execute_ipa_summary_passes(all_lto_gen_passes)
      ipa_write_summaries
   execute_ipa_pass_list(all_late_ipa_passes)
   cgraph_expand_all_functions
      cgraph_expand_function
      /* Intraprocedural passes on GIMPLE, */
      /* expansion pass, and passes on RTL. */
```

Partitioned LTO (aka WHOPR LTO)

Option `-flto -c`



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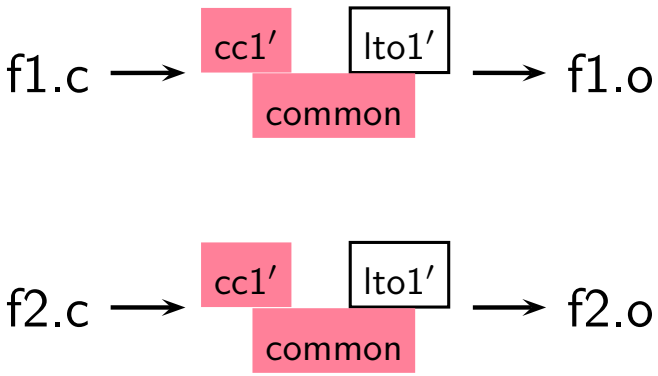
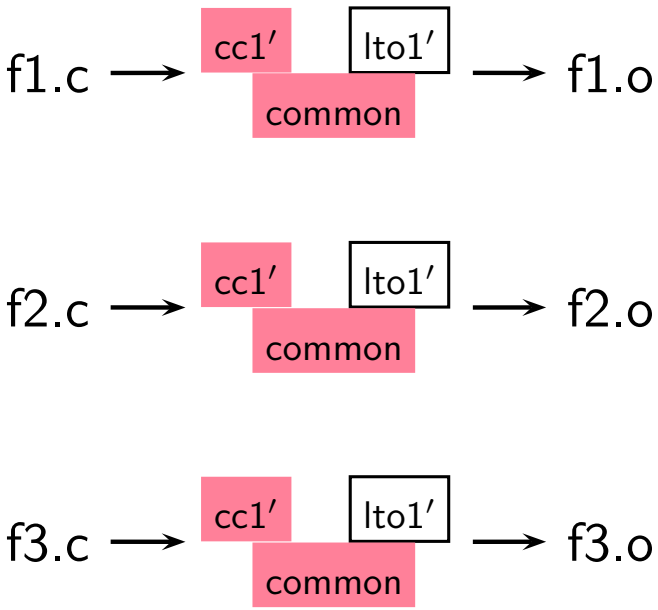
Option `-flto -c`

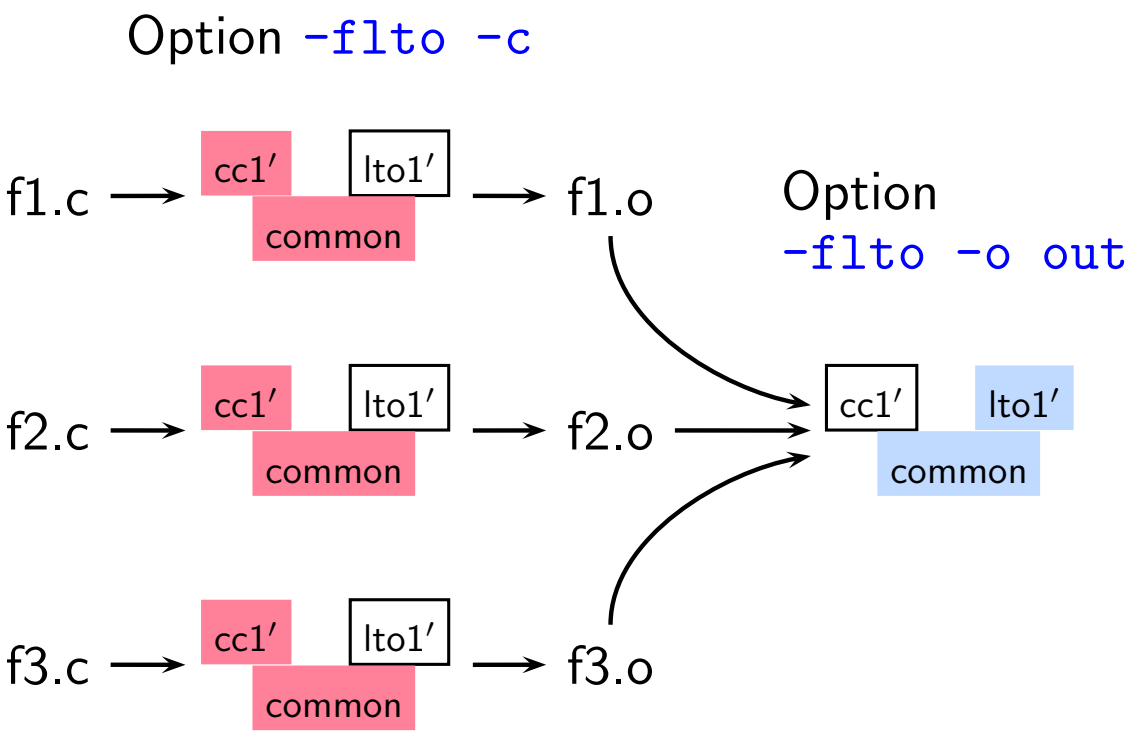


Partitioned LTO (aka WHOPR LTO)

Option `-flto -c`



Partitioned LTO (aka WHOPR LTO)



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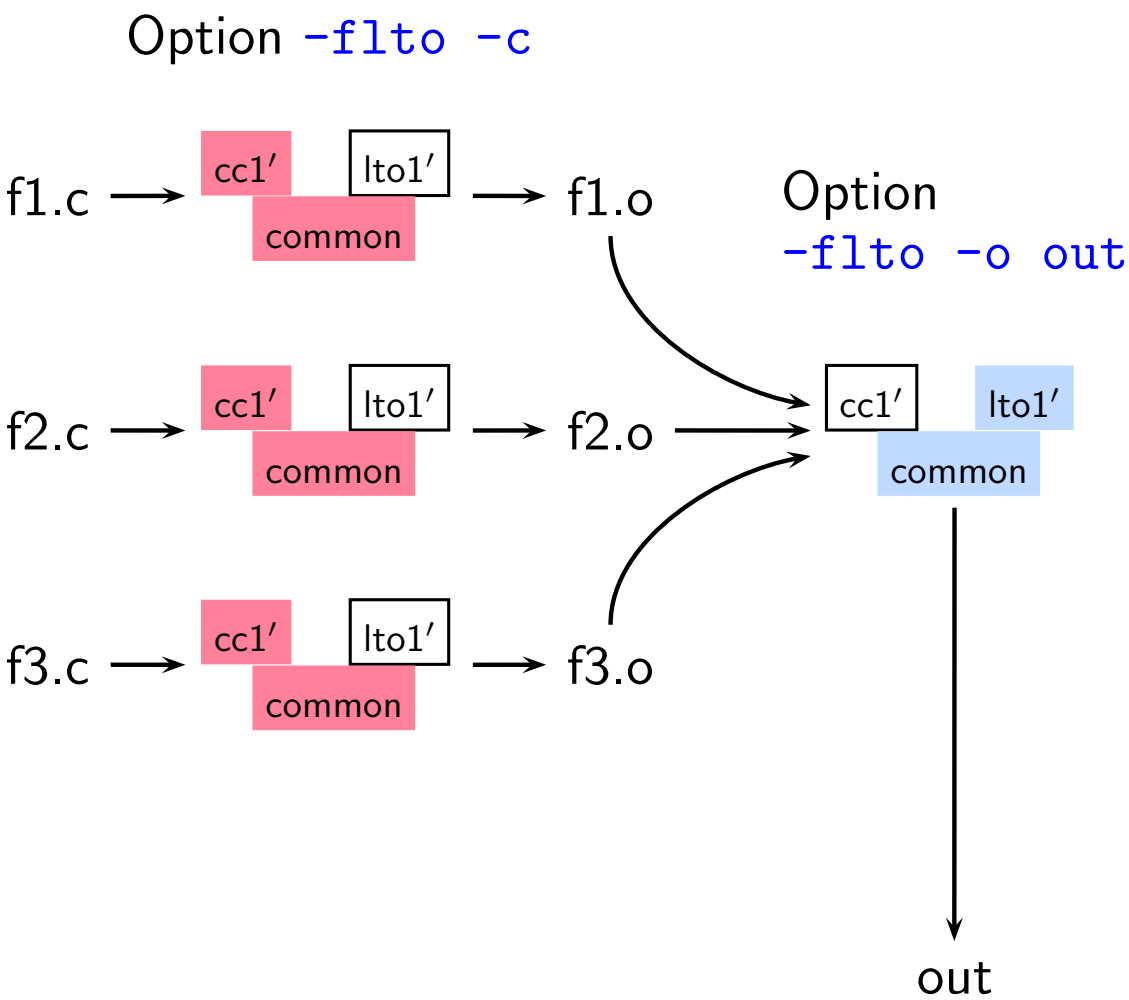

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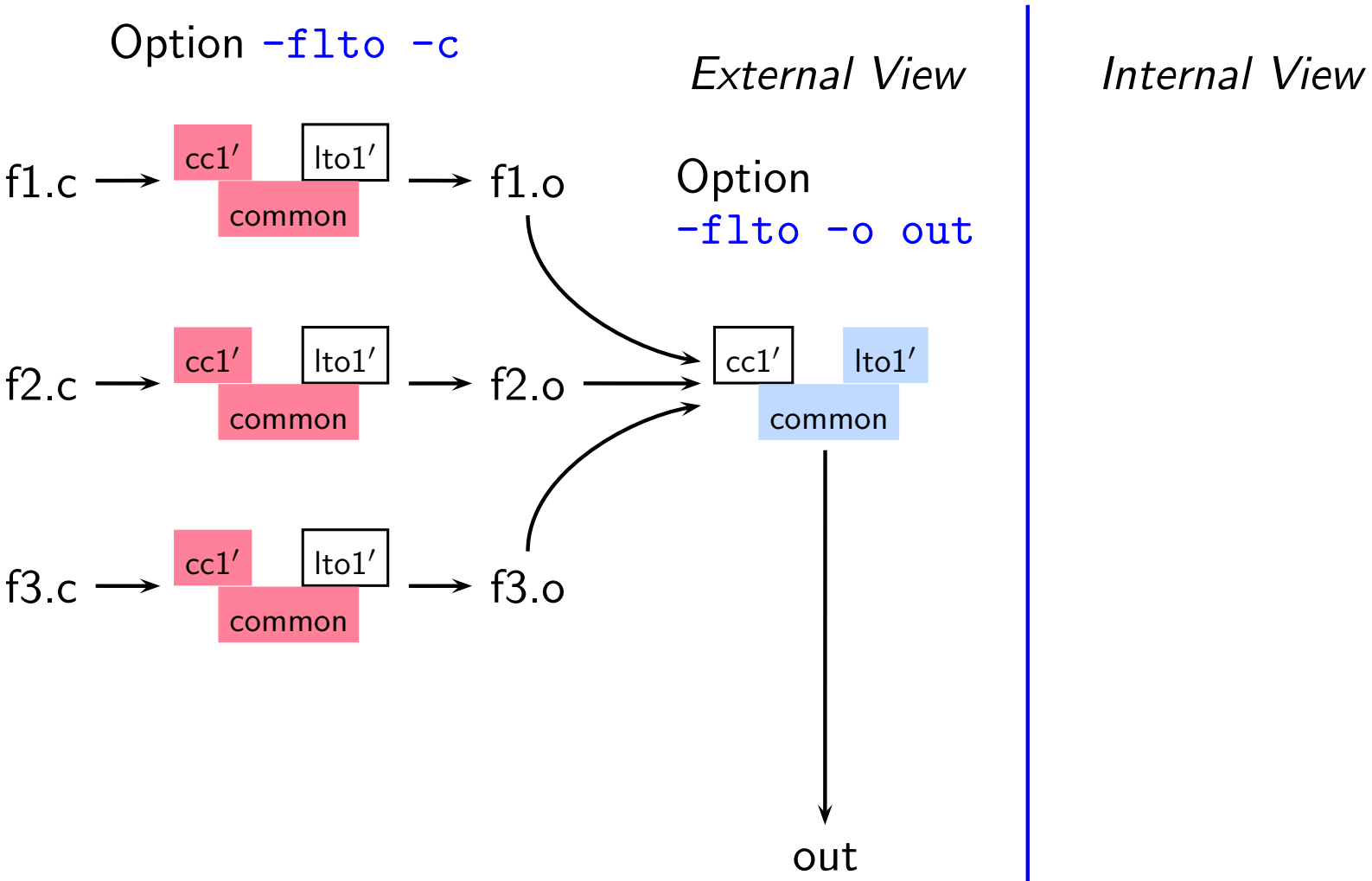

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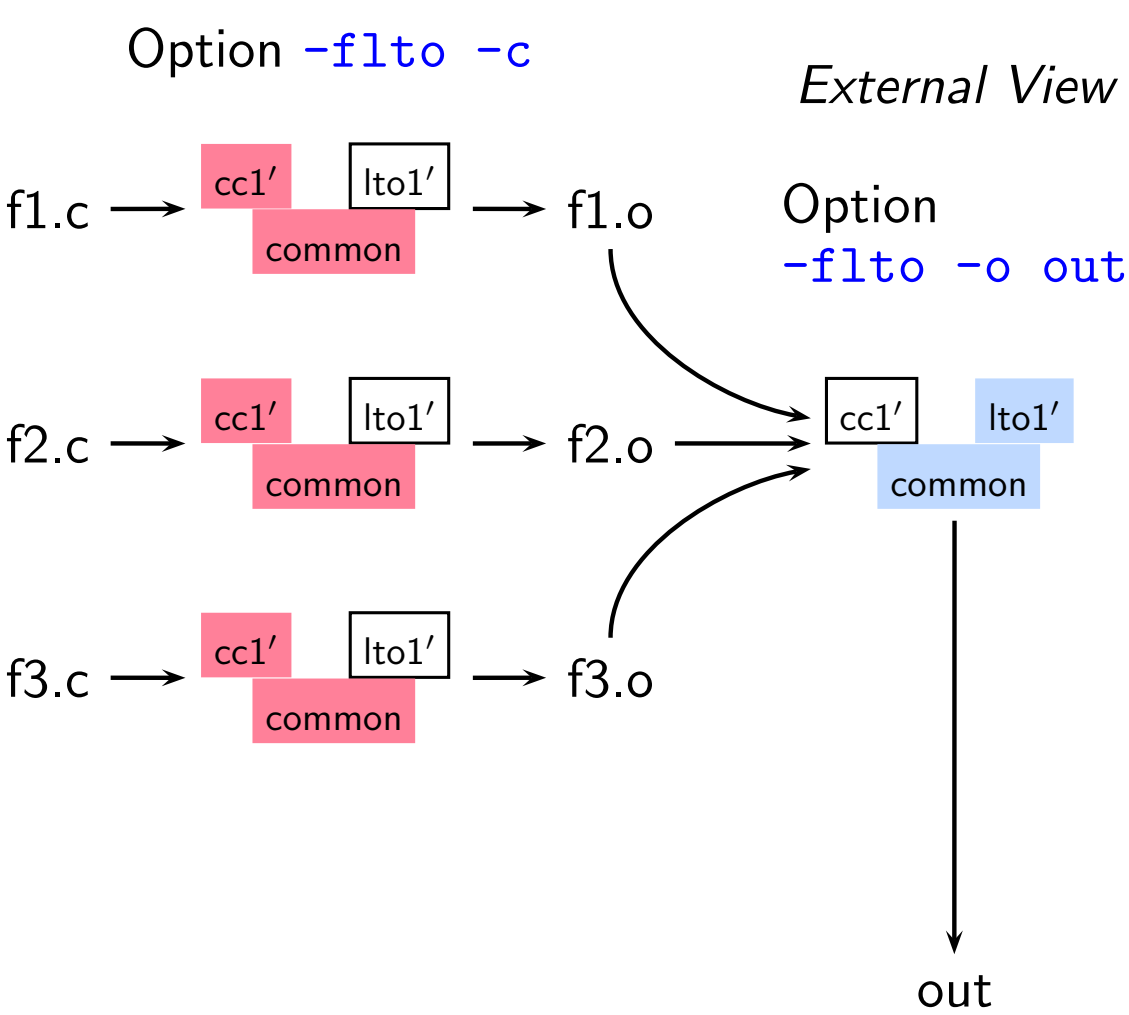
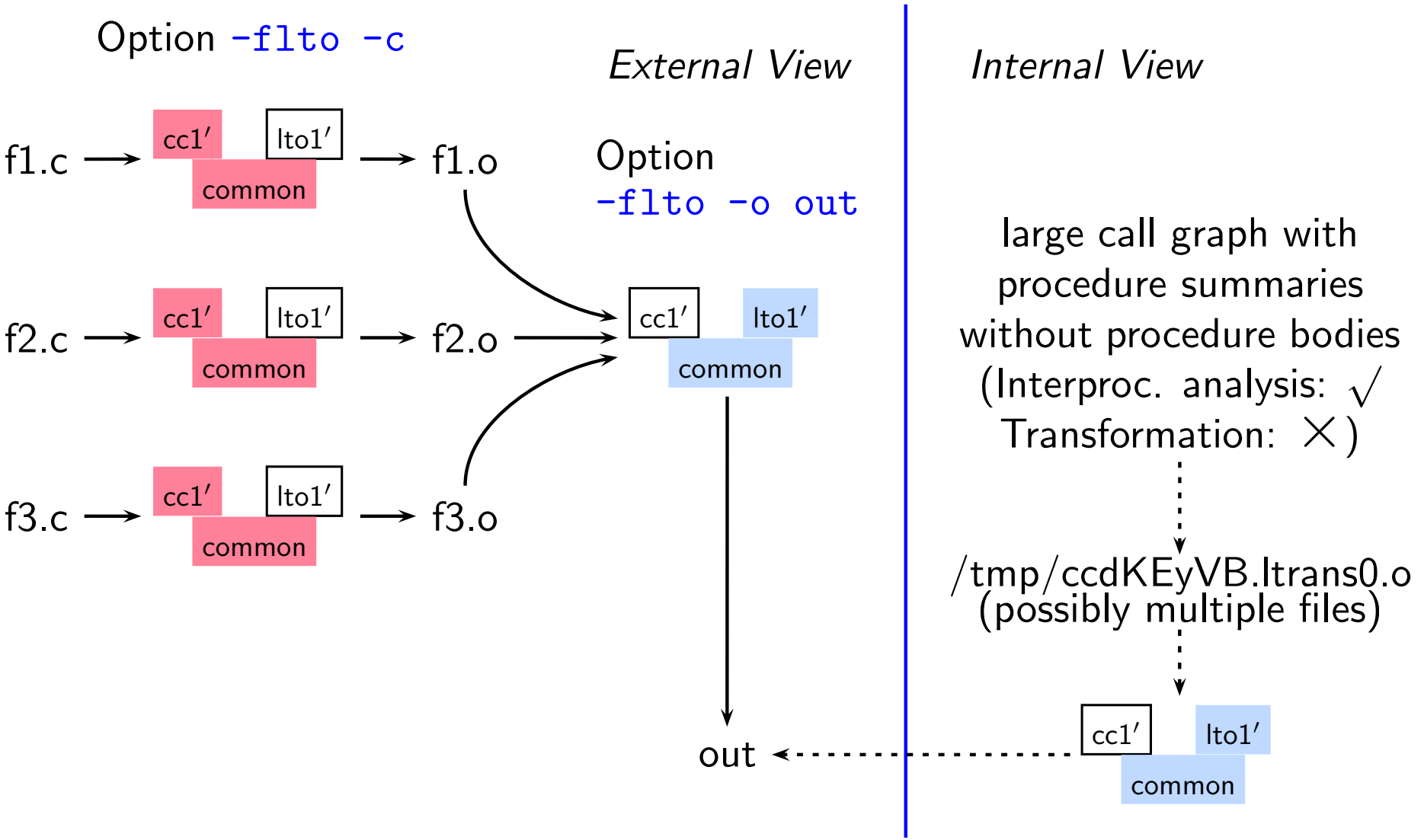


Internal View

large call graph with procedure summaries without procedure bodies (Interproc. analysis: $\surd$ Transformation: $\times$)

/tmp/ccdKEyVB.ltrans0.o (possibly multiple files)

Partitioned LTO (aka WHOPR LTO)



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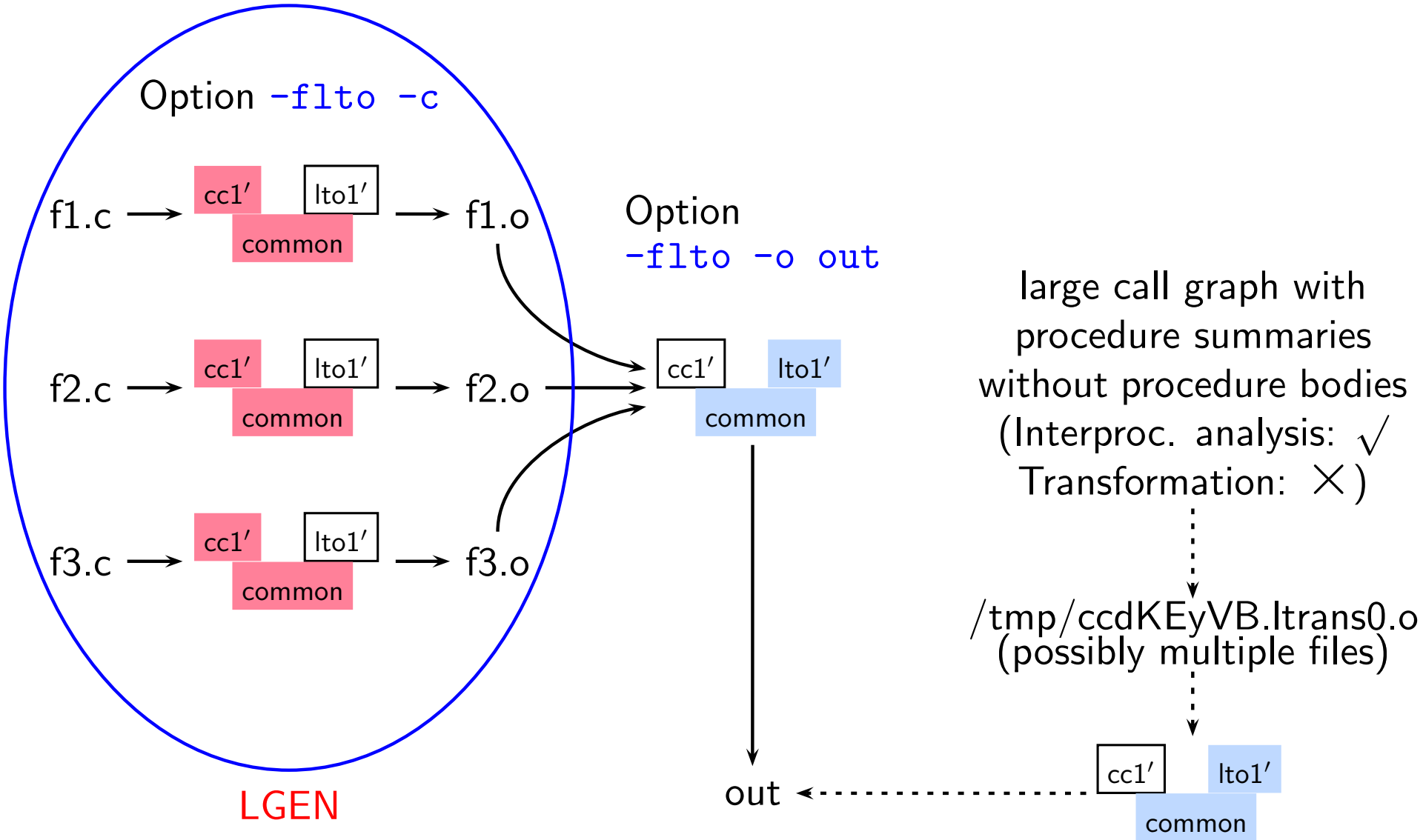

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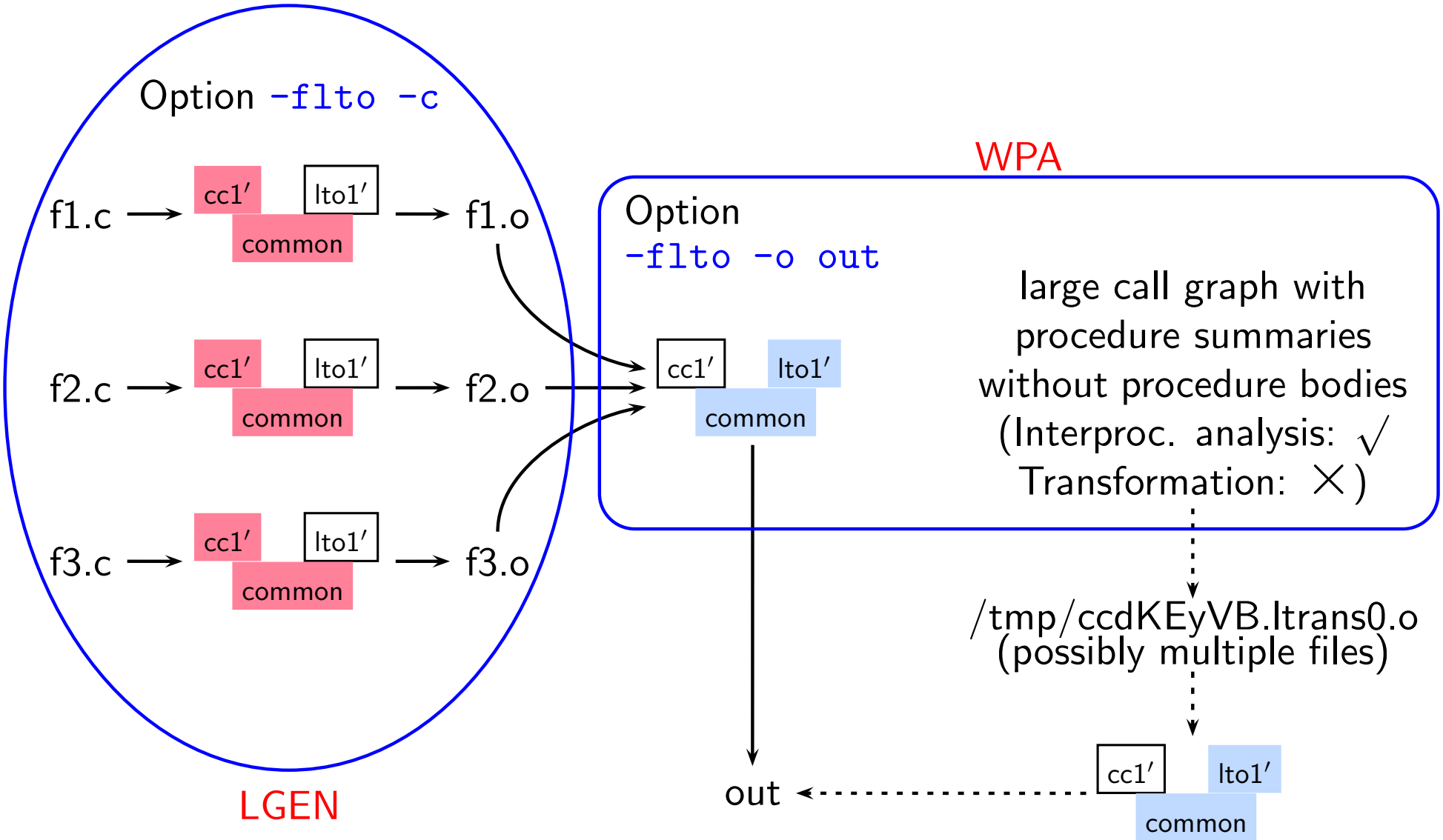
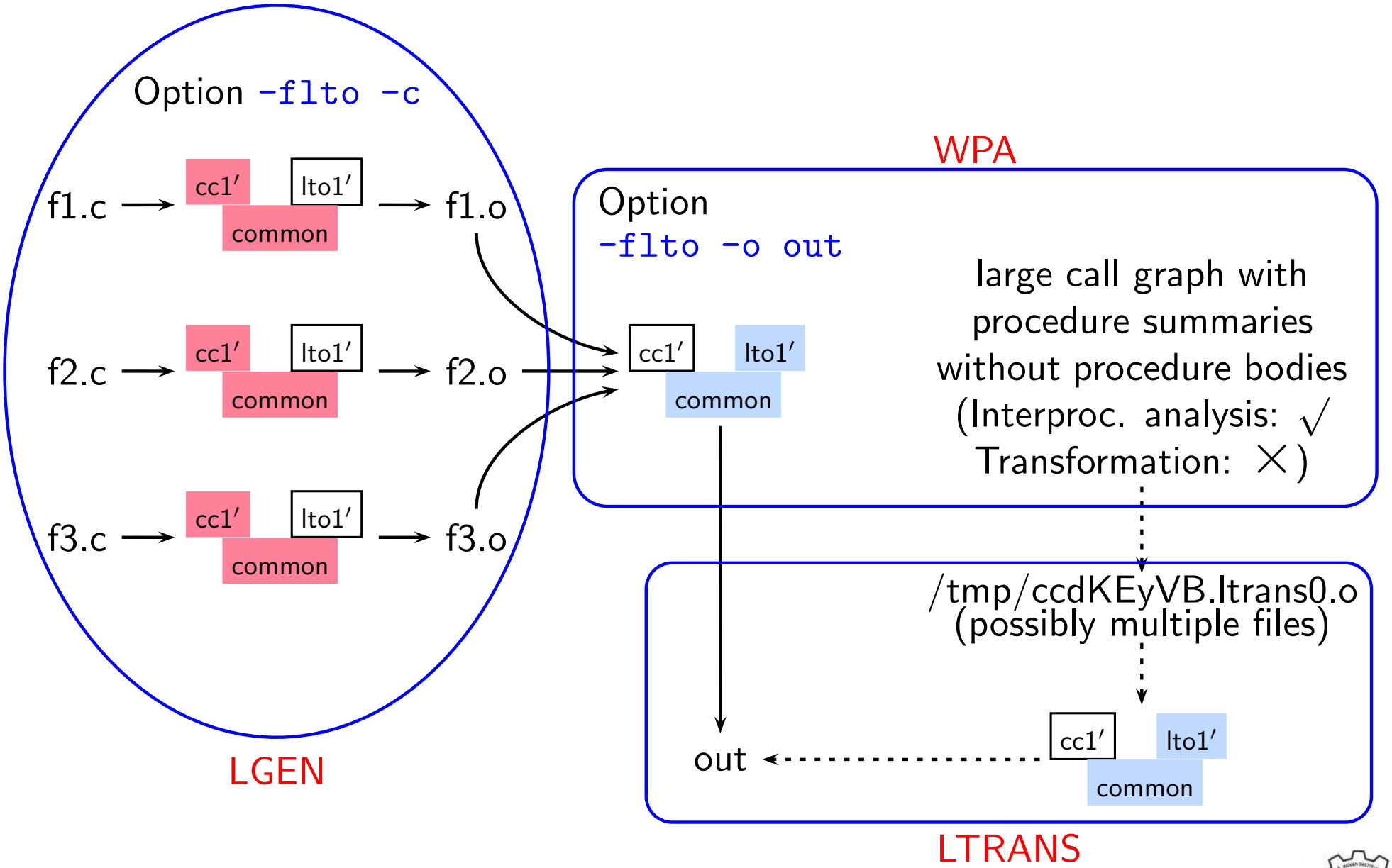
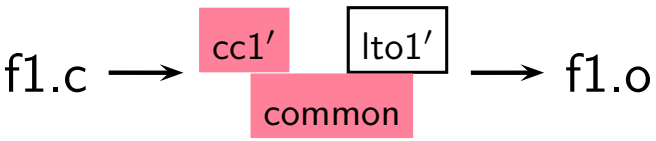


Partitioned LTO (aka WHOPR LTO)



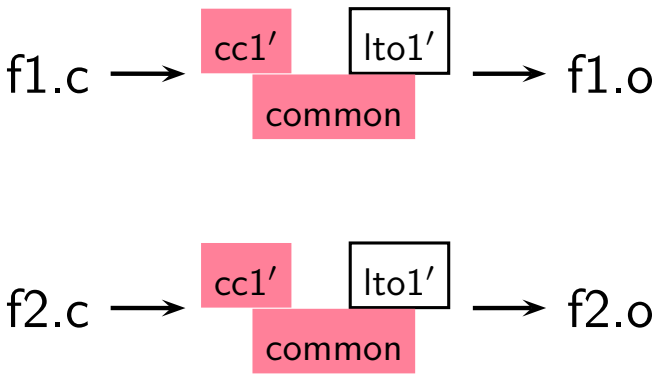
Non-Partitioned LTO

Option `-flto -c`



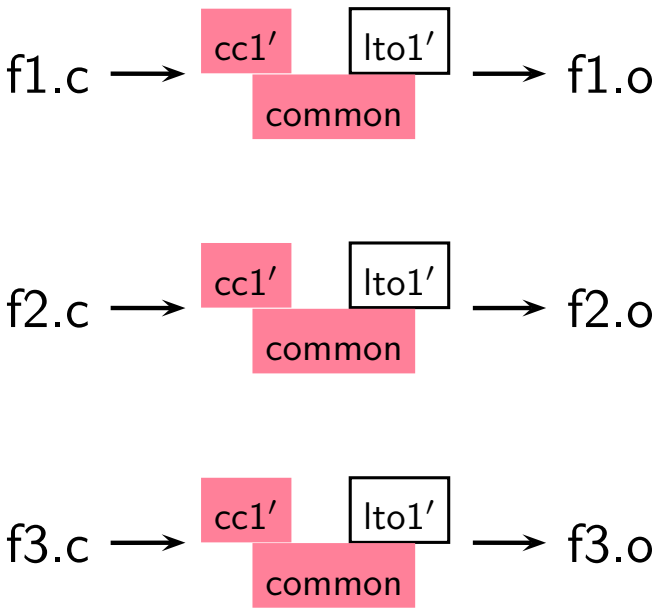
Non-Partitioned LTO

Option `-flto -c`

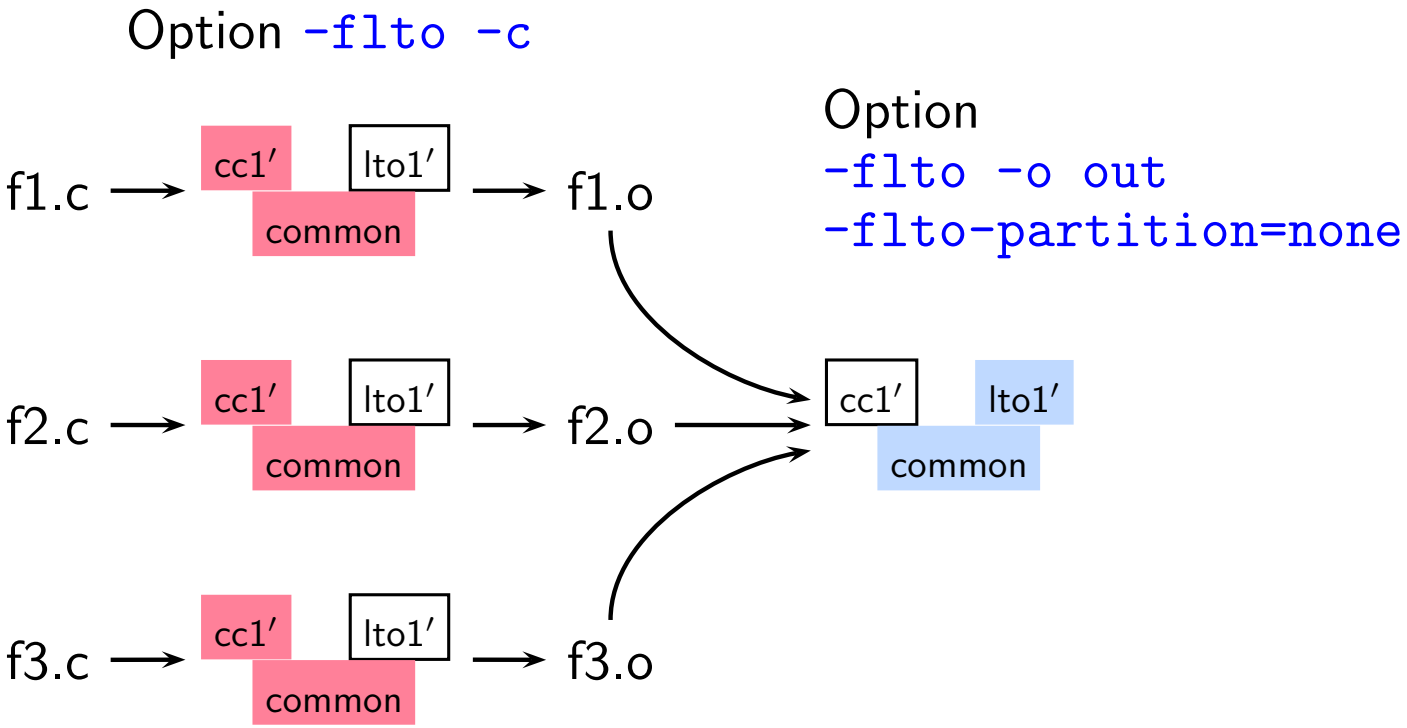


Non-Partitioned LTO

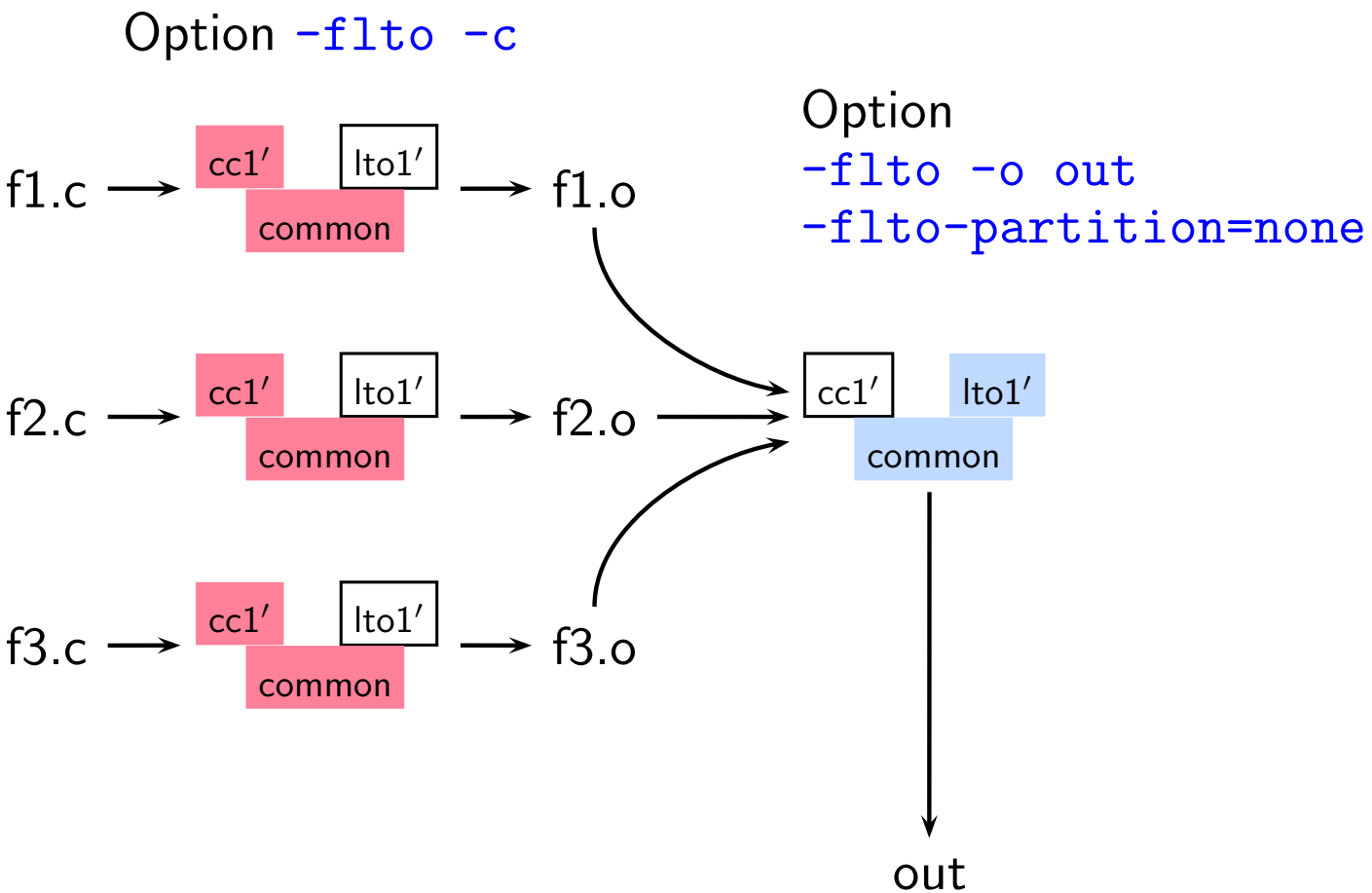
Option `-flto -c`



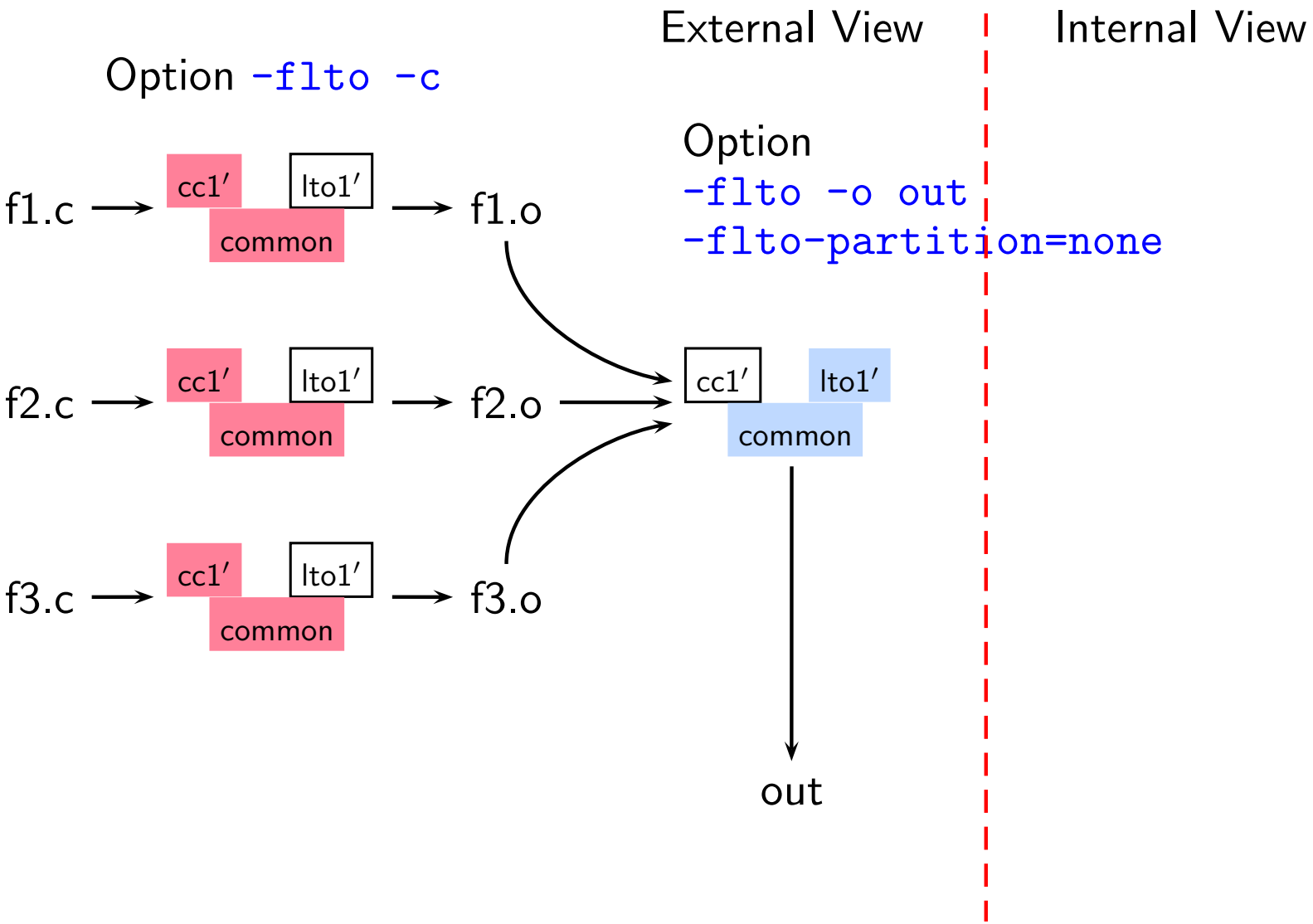
Non-Partitioned LTO



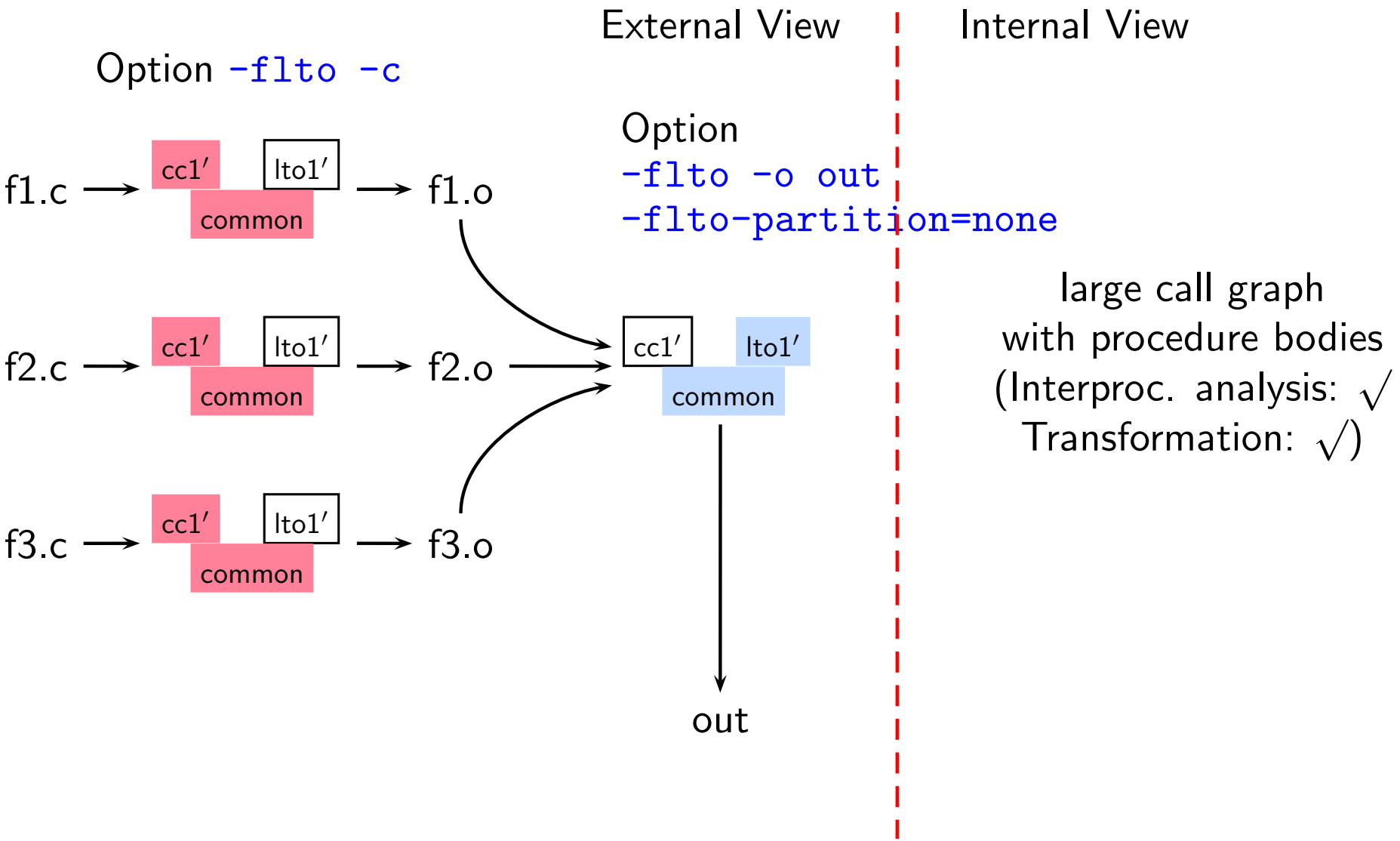
Non-Partitioned LTO



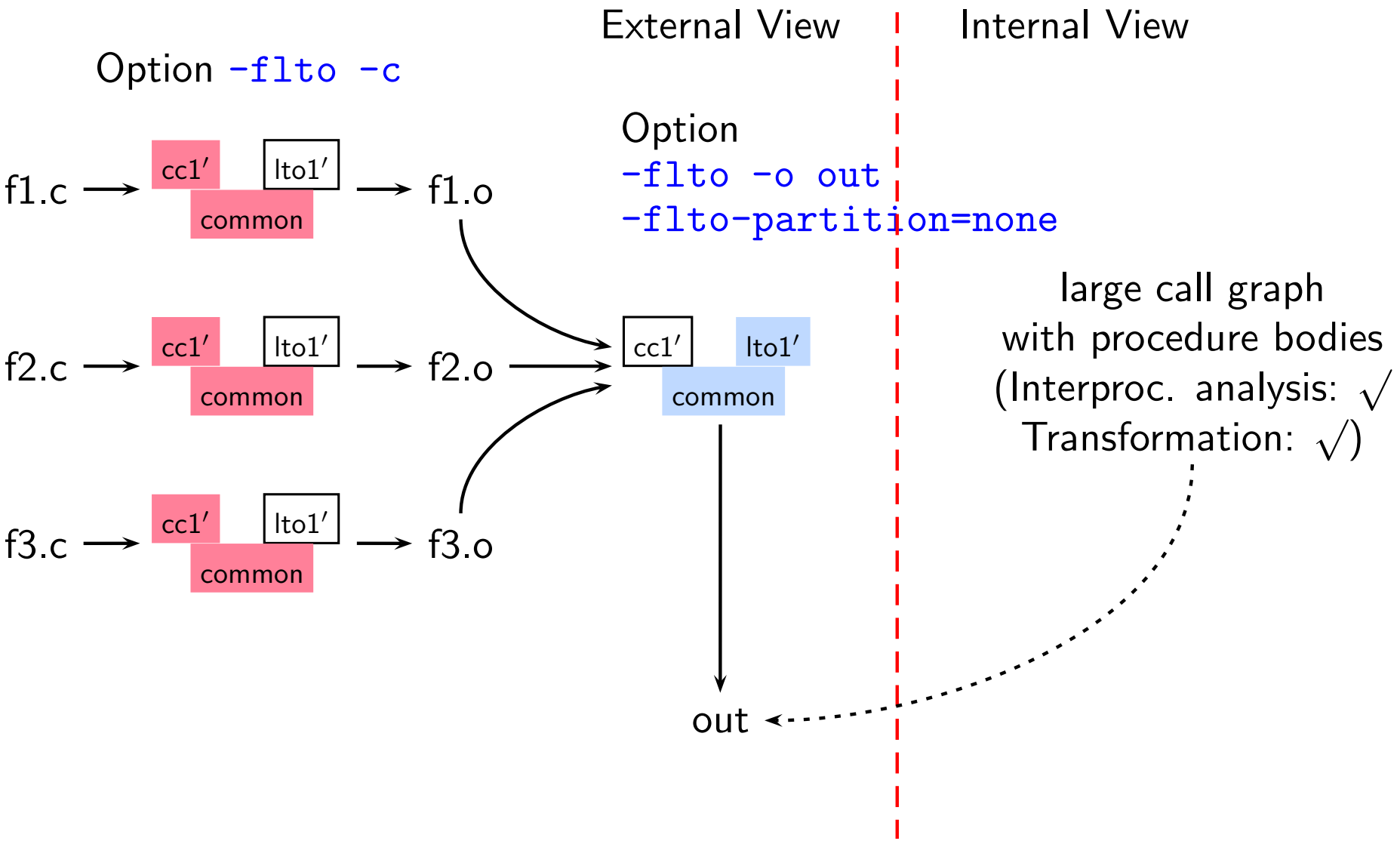
Non-Partitioned LTO



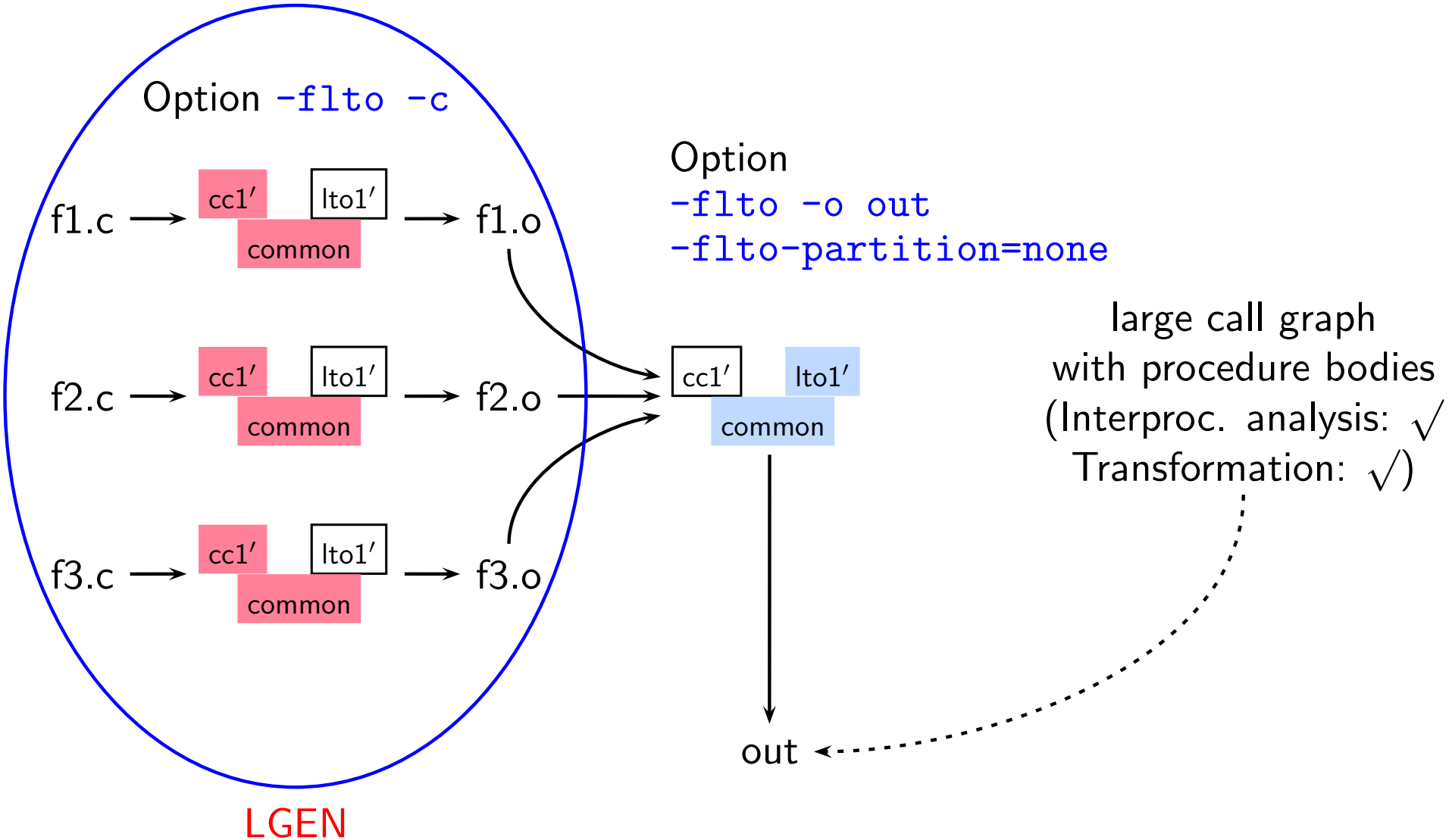
Non-Partitioned LTO



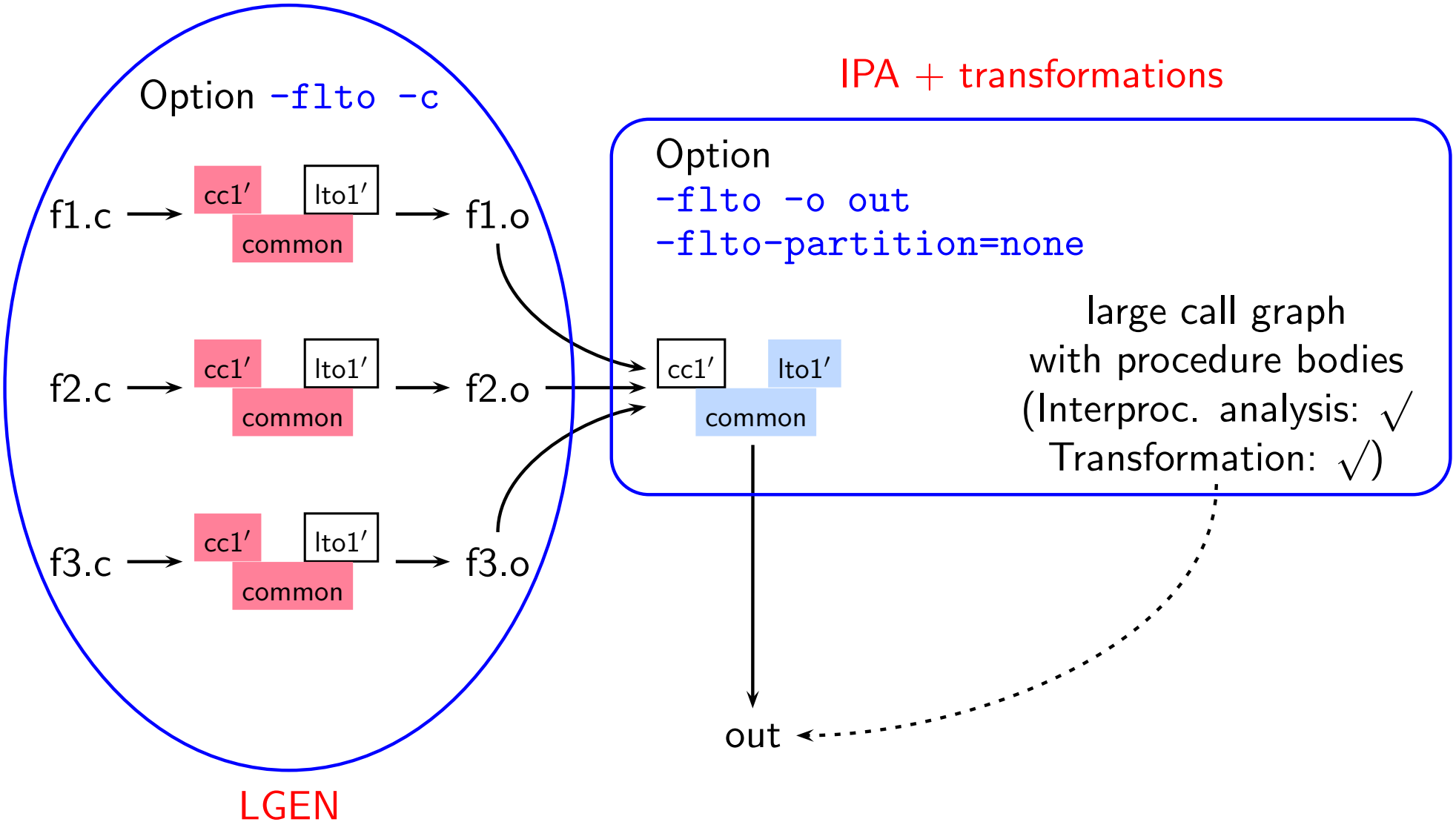
Non-Partitioned LTO



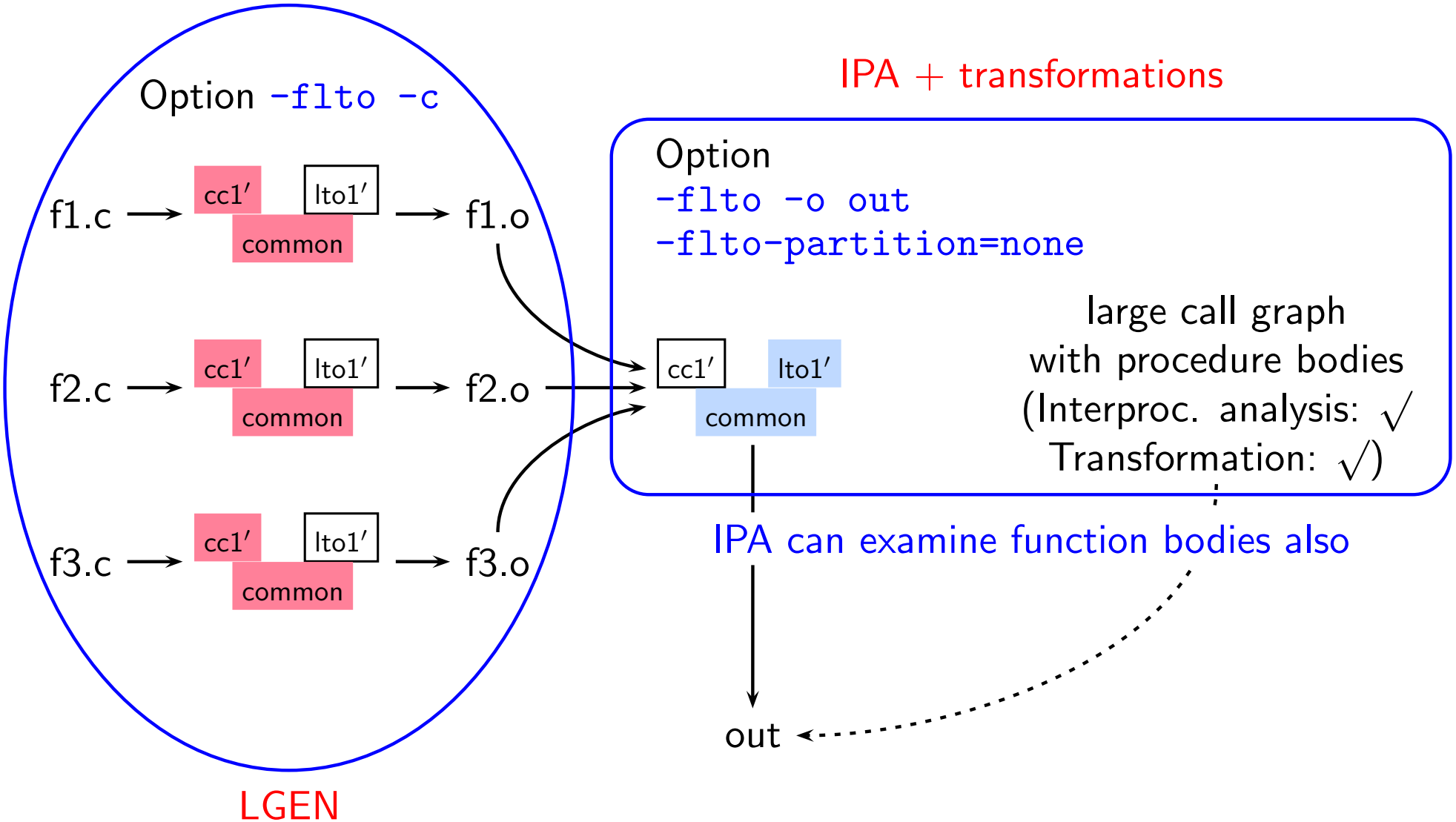
Non-Partitioned LTO



Non-Partitioned LTO



Non-Partitioned LTO



Part 6

Conclusions

Conclusions

- Excellent mechanism of plugging in different
  - translators in the main driver
  - front ends, passes, and back ends in the main compiler
- However, the plugins have been used in an adhoc manner
- LTO is a good support for interprocedural analysis and optimization

  It would be useful to support an LTO mode that
  - creates a large call graph of the entire program with
  - on-demand loading of procedure bodies for
  - enabling examining procedure bodies for interprocedural analysis