

Meta Large Language Model Compiler: Foundation Models of Compiler Optimization

Arxiv

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INLINING OPTIMIZATIONS CAN BE SURPRISING 2

```
Struct Loop_Slow() {  
    Struct s = new();  
    for(int i = 0; i < 1000; i++)  
        s = Add(s);  
    return s;  
}  
static Struct Add(Struct v) {  
    var a = v.A + v.A;  
    return new(a, a);  
}
```

```
Struct Loop_Fast() {  
    Struct s = new();  
    for(int i = 0; i < 1000; i++)  
        s = Add(s,0);  
    return s;  
}  
static Struct Add(Struct v, int x) {  
    var a = v.A + v.A;  
    return new(a, a);  
}
```

Method	Mean	Error	StdDev
Loop_Slow	10.475 us	0.1069 us	0.0893 us
Loop_Fast	2.092 us	0.0302 us	0.0282 us

Compilation Pipeline

- Source Code (*.c, *.cpp)
- Abstract Syntax Tree
- Intermediate Representation
- Binary

Intermediate Representation



```
define dso_local i32 @main() #0 {  
    call void @srand(i32 2019) #4  
    br label %1  
  
1:                                     ; preds = %5, %0  
    %2 = phi i32 [ 0, %0 ], [ %9, %5 ]  
    %3 = icmp slt i32 %2, 10  
    br i1 %3, label %5, label %4  
  
4:                                     ; preds = %1  
    ret i32 0  
  
5:                                     ; preds = %1  
    %6 = call i32 @rand() #4  
    %7 = srem i32 %6, 3  
    %8 = call i32 (i8*, ...) @printf(i8* getelementptr inbounds ([4 x i8], [4 x i8]* @.str, i64 0, i64 0), i32  
%7)  
    %9 = add nsw i32 %2, 1  
    br label %1  
}
```

LLM Compiler

- Training LLMs is resource-intensive
- LLM Compiler, openly available pre-trained models designed for code optimization tasks.
- Two models
 - LLM Compiler (7B, 13B)
 - LLM Compiler FTD (7B, 13B)

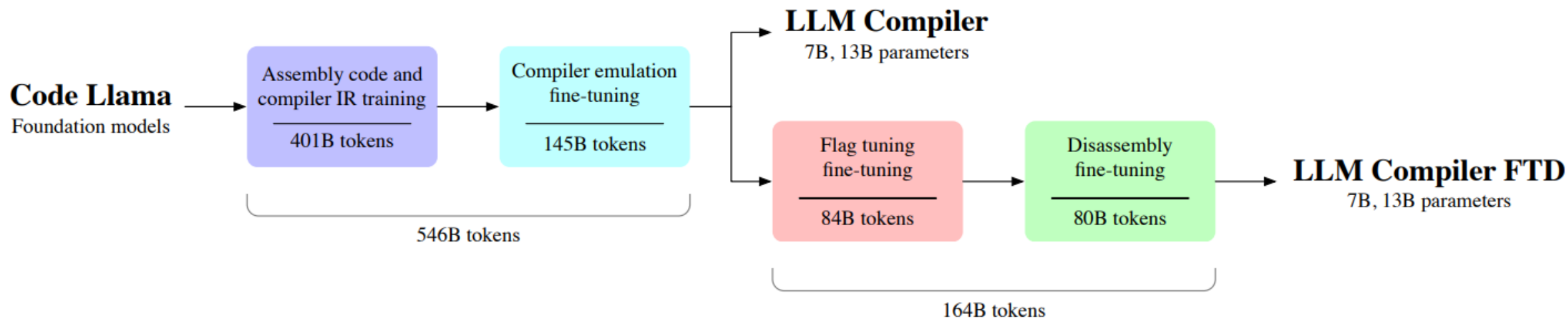


Figure 1: LLM COMPILER models are specialized from CODE LLAMA by training on 546 billion tokens of compiler-centric data in two stages. In the first stage the models are trained predominantly on unlabelled compiler IRs and assembly code. In the next stage the models are instruction fine-tuned to predict the output and effect of optimizations. LLM COMPILER FTD models are then further fine-tuned on 164 billion tokens of downstream flag tuning and disassembly task datasets, for a total of 710 billion training tokens. During each of the four stages of training, 15% of data from the previous tasks is retained.

Dataset

- Coding LLMs are typically trained with
 - Largely high level source language (Python)
 - Assembly (small)
 - Compiler IR (really small)
- Compiler Centric Dataset needed

Dataset	Sampling prop.	Epochs	Disk size
IR and assembly pretraining (401 billion tokens)			
Code	85.00%	1.000	872 GB
Natural language related to code	14.00%	0.019	942 GB
Natural language	1.00%	0.001	938 GB
Compiler emulation (additional 145 billion tokens)			
Compiler emulation	85.00%	1.702	175 GB
Code	13.00%	0.055	872 GB
Natural language related to code	1.80%	0.001	942 GB
Natural language	0.20%	6.9e−5	938 GB
Flag tuning fine-tuning (additional 84 billion tokens)			
Flag tuning	85.00%	1.700	103 GB
Compiler emulation	11.73%	0.136	175 GB
Code	2.84%	0.007	872 GB
Natural language related to code	0.40%	1.1e−4	942 GB
Natural language	0.03%	8.8e−6	938 GB
Disassembly fine-tuning (additional 80 billion tokens)			
Disassembly	85.00%	1.707	88 GB
Flag tuning	4.68%	0.089	103 GB
Compiler emulation	8.07%	0.089	175 GB
Code	1.96%	0.004	872 GB
Natural language related to code	0.27%	7.5e−5	942 GB
Natural language	0.03%	5.7e−6	938 GB

Table 1: Training datasets used.

Training Tasks

- Compiler emulation (fine tuning)
- Flag tuning (fine tuning)
- Disassembly (fine tuning)

Compiler Emulation

- Emulate Compiler
 - Emit Optimized IR
 - Emit Assembly
- Dataset
 - 1~50 optimization passes applied
 - Pass chosen randomly

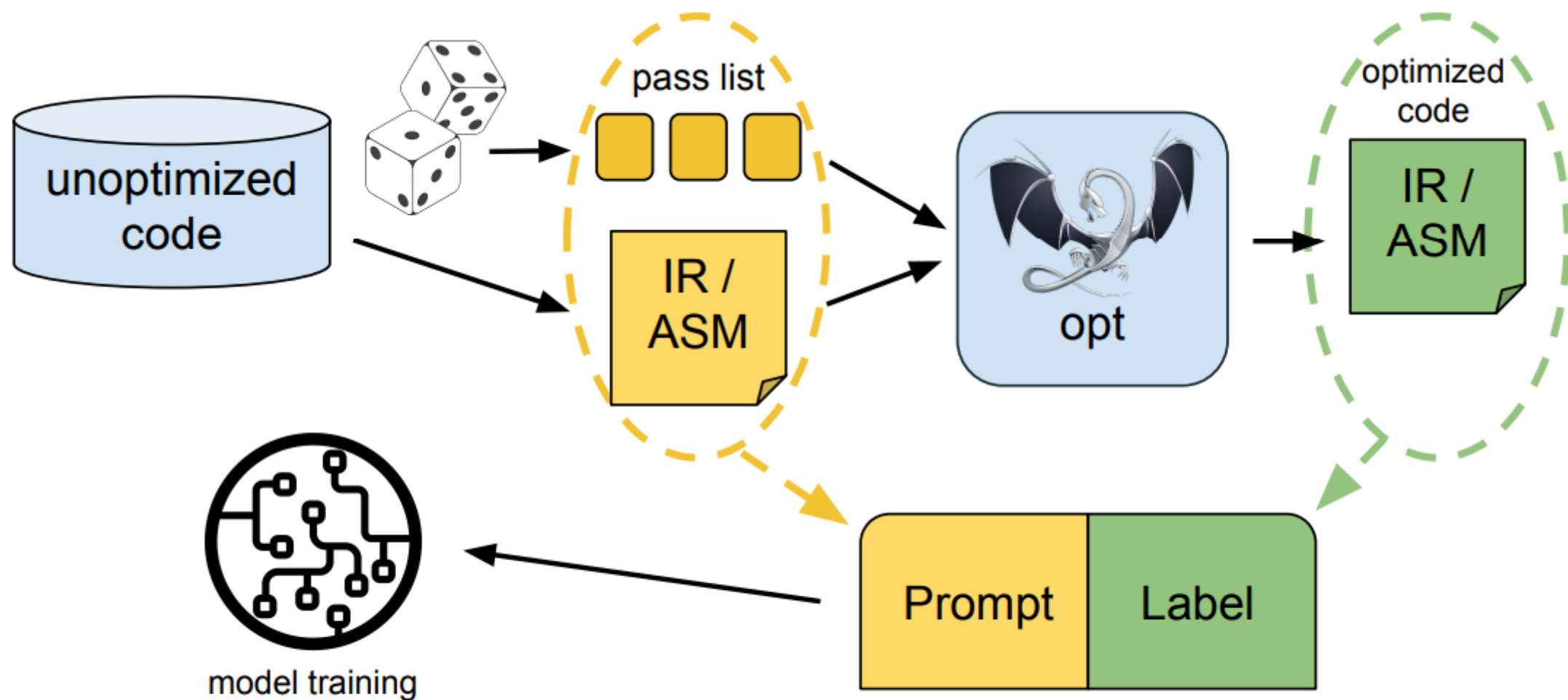


Figure 2: To give the model an understanding of how compiler optimizations work, we use *compiler emulation*. Unoptimized code samples and random pass lists are given to `opt` to generate optimized code (IR or assembly). Pass list and input code are taken together as prompt while the generated output code is used as label.

B.1 Compiler emulation prompts

Prompt:

[INST] Give the LLVM-IR for the following code when optimized using `opt -p 'module(default<0z>）'`:

```
<code>; ModuleID = '<stdin>'
source_filename = "-"
target datalayout = "e-m:e-p270:32:32-p271:32:32-p272:64:64-i64:64-f80:128-n8:16:32:64-S128"
target triple = "x86_64-unknown-linux-gnu"

; Function Attrs: minsize nounwind optsize uwtable
define dso_local i32 @add_two(i32 noundef %0, i32 noundef %1) #0 {
    %3 = alloca i32, align 4
    %4 = alloca i32, align 4
    store i32 %0, ptr %3, align 4, !tbaa !5
    store i32 %1, ptr %4, align 4, !tbaa !5
    %5 = load i32, ptr %3, align 4, !tbaa !5
    %6 = load i32, ptr %4, align 4, !tbaa !5
    %7 = add nsw i32 %5, %6
    ret i32 %7
}

attributes #0 = { minsize nounwind optsize uwtable "min-legal-vector-width"="0" "no-trapping-math"="true"
    ↪ "stack-protector-buffer-size"="8" "target-cpu"="x86-64" "target-features"="+cmov,+cx8,+fxsr,+mmx,+sse
    ↪ ,+sse2,+x87" "tune-cpu"="generic" }

!llvm.module.flags = !{!0, !1, !2, !3}
!llvm.ident = !{!4}

!0 = !{i32 1, !"wchar_size", i32 4}
!1 = !{i32 8, !"PIC Level", i32 2}
!2 = !{i32 7, !"PIE Level", i32 2}
!3 = !{i32 7, !"uwtable", i32 2}
!4 = !{!"clang version 17.0.6 (git@github.com:fairinternal/CodeGen.git
    ↪ b05db9bbf7a92019267416c1bb9996fe6134e3f1)"}
!5 = !{!6, !6, i64 0}
!6 = !{!"int", !7, i64 0}
!7 = !{!"omnipotent char", !8, i64 0}
!8 = !{!"Simple C/C++ TBAA"}
</code>
```

The input code has instruction count 8 and binary size 65 bytes. [/INST]

Answer:

The LLVM-IR will have instruction count 2 and binary size 53 bytes:

```
<code>; ModuleID = '<stdin>'
source_filename = "-"
target datalayout = "e-m:e-p270:32:32-p271:32:32-p272:64:64-i64:64-f80:128-n8:16:32:64-S128"
target triple = "x86_64-unknown-linux-gnu"

; Function Attrs: minsize mustprogress norecurse nosync nounwind optsize willreturn memory(none)
→ uwtable
define dso_local i32 @add_two(i32 noundef %0, i32 noundef %1) local_unnamed_addr #0 {
    %3 = add nsw i32 %1, %0
    ret i32 %3
}

attributes #0 = { minsize mustprogress norecurse nosync nounwind optsize willreturn memory(none)
→ uwtable "min-legal-vector-width"="0" "no-trapping-math"="true" "stack-protector-buffer-size"="8" "
→ target-cpu"="x86-64" "target-features"="+cmov,+cx8,+fxsr,+mmx,+sse,+sse2,+x87" "tune-cpu"="generic" }

!llvm.module.flags = !{!0, !1, !2, !3}
!llvm.ident = !{!4}

!0 = !{i32 1, !"wchar_size", i32 4}
!1 = !{i32 8, !"PIC Level", i32 2}
!2 = !{i32 7, !"PIE Level", i32 2}
!3 = !{i32 7, !"uwtable", i32 2}
!4 = !{!"clang version 17.0.6 (git@github.com:fairinternal/CodeGen.git
→ b05db9bbf7a92019267416c1bb9996fe6134e3f1)"}
</code>
```

Listing 2: Prompt used for $IR \rightarrow IR$ compiler emulation.

Prompt:

[INST] Give the assembly for the following code when optimized using `opt -p 'module(default<0z>)'`:

```
<code>; ModuleID = '<stdin>'
source_filename = "-"
target datalayout = "e-m:e-p270:32:32-p271:32:32-p272:64:64-i64:64-f80:128-n8:16:32:64-S128"
target triple = "x86_64-unknown-linux-gnu"

; Function Attrs: minsize nounwind optsize uwtable
define dso_local i32 @add_two(i32 noundef %0, i32 noundef %1) #0 {
    %3 = alloca i32, align 4
    %4 = alloca i32, align 4
    store i32 %0, ptr %3, align 4, !tbaa !5
    store i32 %1, ptr %4, align 4, !tbaa !5
    %5 = load i32, ptr %3, align 4, !tbaa !5
    %6 = load i32, ptr %4, align 4, !tbaa !5
    %7 = add nsw i32 %5, %6
    ret i32 %7
}

attributes #0 = { minsize nounwind optsize uwtable "min-legal-vector-width"="0" "no-trapping-math"="true"
    ↪ "stack-protector-buffer-size"="8" "target-cpu"="x86-64" "target-features"="+cmov,+cx8,+fxsr,+mmx,+sse
    ↪ ,+sse2,+x87" "tune-cpu"="generic" }

!llvm.module.flags = !{!0, !1, !2, !3}
!llvm.ident = !{!4}

!0 = !{i32 1, !"wchar_size", i32 4}
!1 = !{i32 8, !"PIC Level", i32 2}
!2 = !{i32 7, !"PIE Level", i32 2}
!3 = !{i32 7, !"uwtable", i32 2}
!4 = !{!"clang version 17.0.6 (git@github.com:fairinternal/CodeGen.git
    ↪ b05db9bbf7a92019267416c1bb9996fe6134e3f1)"}
!5 = !{!6, !6, i64 0}
!6 = !{!"int", !7, i64 0}
!7 = !{!"omnipotent char", !8, i64 0}
!8 = !{!"Simple C/C++ TBAA"}
</code>
```

The input code has instruction count 8 and binary size 65 bytes. [/INST]

Answer:

The assembly will have instruction count 2 and binary size 53 bytes:

```
<code> .text
.file "-"
.globl add_two                # -- Begin function add_two
.type add_two,@function
add_two:                      # @add_two
.cfi_startproc
# %bb.0:
movl %esi, %eax
addl %edi, %eax
retq
.Lfunc_end0:
.size add_two, .Lfunc_end0-add_two
.cfi_endproc

                                # -- End function
.ident "clang version 17.0.6 (git@github.com:fairinternal/CodeGen.git
↪b05db9bbf7a92019267416c1bb9996fe6134e3f1)"
.section ".note.GNU-stack","",@progbits
.addrsig
</code>
```

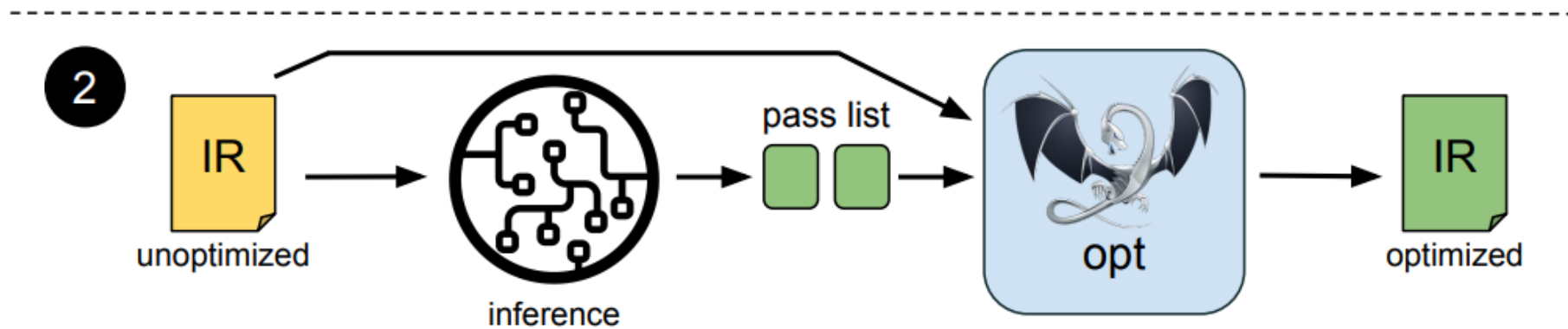
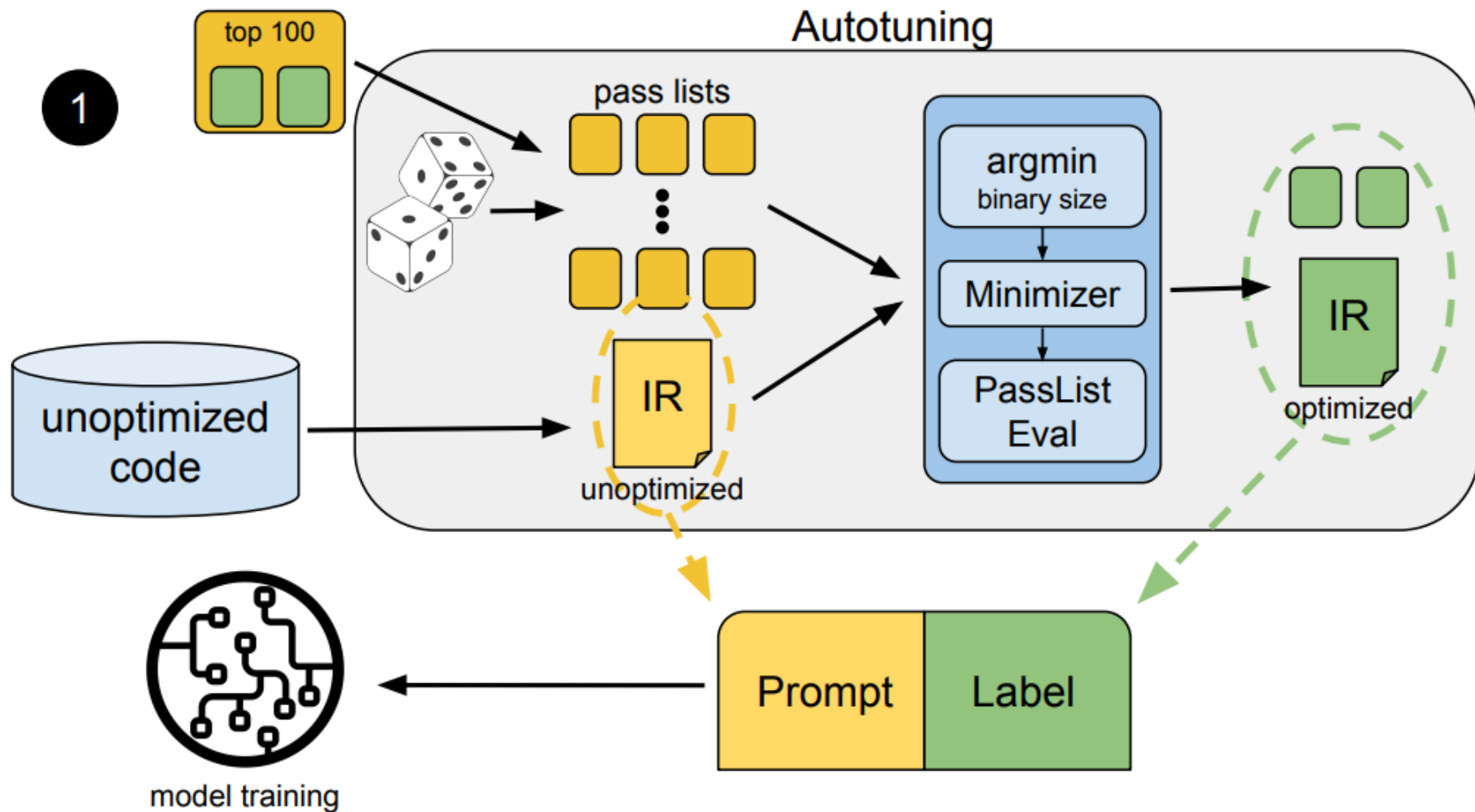
Listing 3: Prompt used for *IR* \rightarrow *assembly* compiler emulation.

Flag Tuning

- Goal of a Compiler
 - Size of the final binary
 - Performance of final binary
 - ...
- LLM Compiler FTD
 - Unoptimized IR (input)
 - List of opt flags that should be applied (output)
- *PassListEval was used to identify pass lists that cause compiler failure

How?

- 1. Unoptimized IR is compiled against multiple random pass lists
- 2. Select pass lists that result with minimum binary size
- 3. Evaluate correctness (PassListEval)
- 4. Final Pass list and optimized IR is used as label in training



Prompt:

[INST] Tell me how to optimize this LLVM-IR for object file size:

```
<code>; ModuleID = '<stdin>'
source_filename = "-"
target_datalayout = "e-m:e-p270:32:32-p271:32:32-p272:64:64-i64:64-f80:128-n8:16:32:64-S128"
target_triple = "x86_64-unknown-linux-gnu"

; Function Attrs: minsize nounwind optsize uwtable
define dso_local i32 @add_two(i32 noundef %0, i32 noundef %1) #0 {
    %3 = alloca i32, align 4
    %4 = alloca i32, align 4
    store i32 %0, ptr %3, align 4, !tbaa !5
    store i32 %1, ptr %4, align 4, !tbaa !5
    %5 = load i32, ptr %3, align 4, !tbaa !5
    %6 = load i32, ptr %4, align 4, !tbaa !5
    %7 = add nsw i32 %5, %6
    ret i32 %7
}

attributes #0 = { minsize nounwind optsize uwtable "min-legal-vector-width"="0" "no-trapping-math"="true"
  ↪ "stack-protector-buffer-size"="8" "target-cpu"="x86-64" "target-features"="+cmov,+cx8,+fxsr,+mmx,+sse
  ↪ ,+sse2,+x87" "tune-cpu"="generic" }

!llvm.module.flags = !{!0, !1, !2, !3}
!llvm.ident = !{!4}

!0 = !{i32 1, !"wchar_size", i32 4}
!1 = !{i32 8, !"PIC Level", i32 2}
!2 = !{i32 7, !"PIE Level", i32 2}
!3 = !{i32 7, !"uwtable", i32 2}
!4 = !{"clang version 17.0.6 (git@github.com:fairinternal/CodeGen.git
  ↪ b05db9bbf7a92019267416c1bb9996fe6134e3f1)"}
!5 = !{!6, !6, i64 0}
!6 = !{"int", !7, i64 0}
!7 = !{"omnipotent char", !8, i64 0}
!8 = !{"Simple C/C++ TBAA"}</code> [/INST]
```

Answer:

The code has object file size of 65 which can be reduced to 53 by running:

```
'opt -p 'module(default<0z>)''
```

This will produce code:

Disassembly

- Assembly -> IR
- Correctness?
 - Verifying equivalence is hard
 - Round tripping: If we generate assembly using the IR and acquire the original assembly (assume correct)
- LLM Compiler FTD
 - Assembly Code (input)
 - Corresponding Disassembled IR (output)

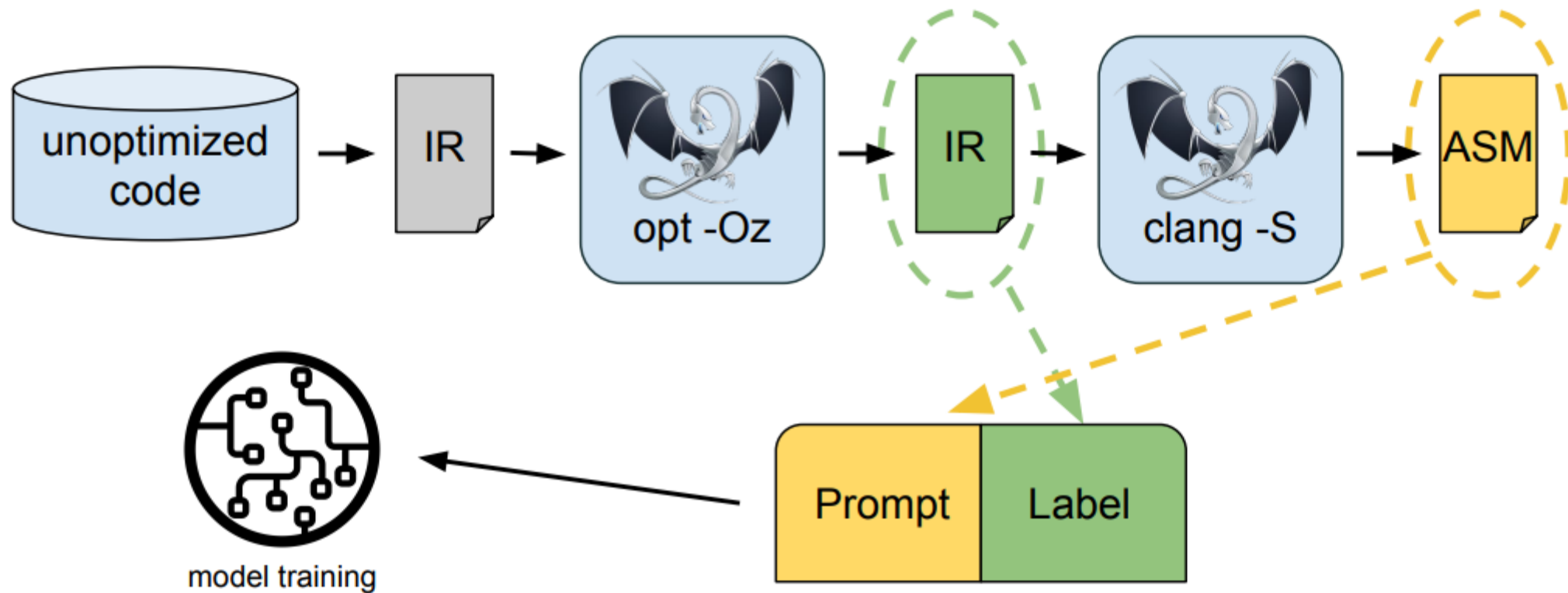


Figure 5: We train the model to understand the relationship between assembly and IR by training it to disassemble a given code sample to its corresponding IR. The IR used to label this training task was generated by optimizing an IR with the `-Oz` flag.

Prompt:

[INST] Disassemble this code to LLVM-IR:

```
<code> .text
.file "-"
.globl add_two                # -- Begin function add_two
.type add_two,@function
add_two:                      # @add_two
.cfi_startproc
# %bb.0:
movl %edi, -4(%rsp)
movl %esi, -8(%rsp)
movl -4(%rsp), %eax
addl -8(%rsp), %eax
retq
.Lfunc_end0:
.size add_two, .Lfunc_end0-add_two
.cfi_endproc

                                # -- End function
.ident "clang version 17.0.6 (git@github.com:fairinternal/CodeGen.git
↪b05db9bbf7a92019267416c1bb9996fe6134e3f1)"
.section ".note.GNU-stack","",@progbits
.addrsig
</code> [/INST]
```

Answer:

```
<code>; ModuleID = '<stdin>'
source_filename = "-"
target datalayout = "e-m:e-p270:32:32-p271:32:32-p272:64:64-i64:64-f80:128-n8:16:32:64-S128"
target triple = "x86_64-unknown-linux-gnu"

; Function Attrs: minsize nounwind optsize uwtable
define dso_local i32 @add_two(i32 noundef %0, i32 noundef %1) #0 {
    %3 = alloca i32, align 4
    %4 = alloca i32, align 4
    store i32 %0, ptr %3, align 4, !tbaa !5
    store i32 %1, ptr %4, align 4, !tbaa !5
    %5 = load i32, ptr %3, align 4, !tbaa !5
    %6 = load i32, ptr %4, align 4, !tbaa !5
    %7 = add nsw i32 %5, %6
    ret i32 %7
}

attributes #0 = { minsize nounwind optsize uwtable "min-legal-vector-width"="0" "no-trapping-math"="true"
  ↳ "stack-protector-buffer-size"="8" "target-cpu"="x86-64" "target-features"="+cmov,+cx8,+fxsr,+mmx,+sse
  ↳ ,+sse2,+x87" "tune-cpu"="generic" }

!llvm.module.flags = !{!0, !1, !2, !3}
!llvm.ident = !{!4}

!0 = !{i32 1, !"wchar_size", i32 4}
!1 = !{i32 8, !"PIC Level", i32 2}
!2 = !{i32 7, !"PIE Level", i32 2}
!3 = !{i32 7, !"uwtable", i32 2}
!4 = !{!"clang version 17.0.6 (git@github.com:fairinternal/CodeGen.git
  ↳ b05db9bbf7a92019267416c1bb9996fe6134e3f1)"}
!5 = !{!6, !6, i64 0}
!6 = !{!"int", !7, i64 0}
!7 = !{!"omnipotent char", !8, i64 0}
!8 = !{!"Simple C/C++ TBAA"}
</code>
```

Evaluation: Flag Tuning

- Dataset: MiBench benchmark suite (Guthaus et al. 2001)
- Method
 - Unseen Program (input)
 - Pass List (output)
 - Compare against (-Oz)
- Models
 - GPT-4 Turbo
 - Code Llama Instruct

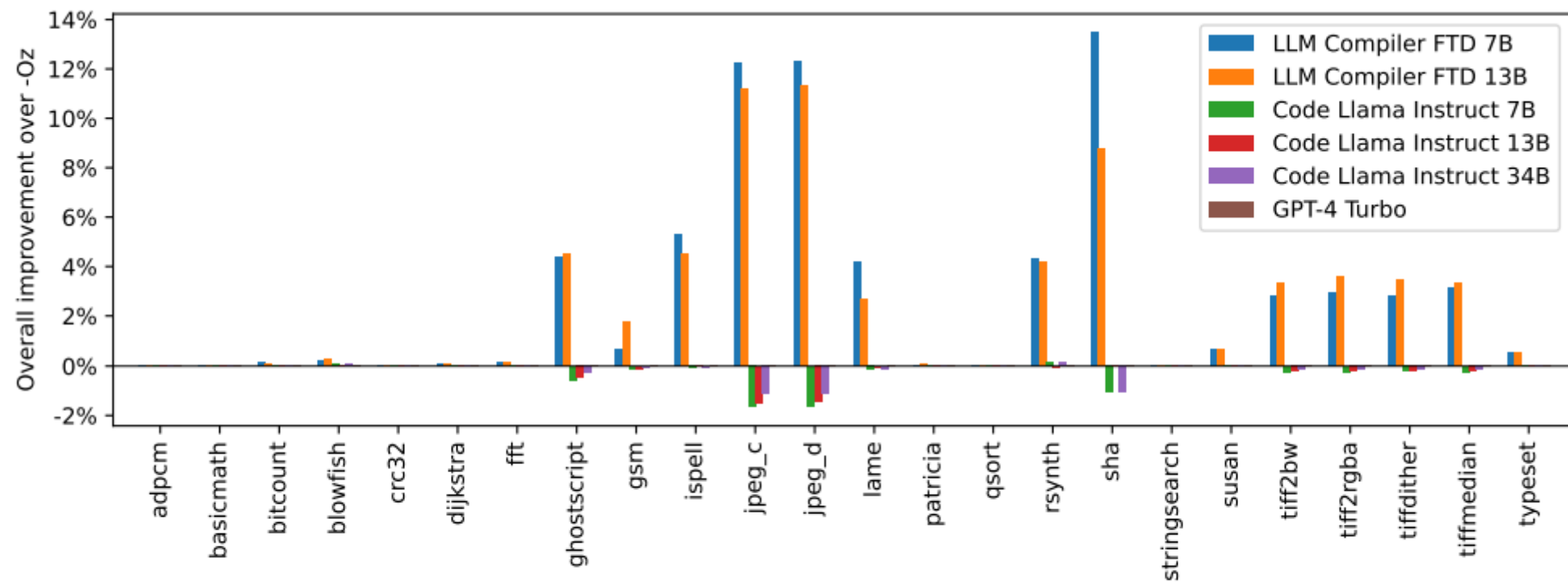
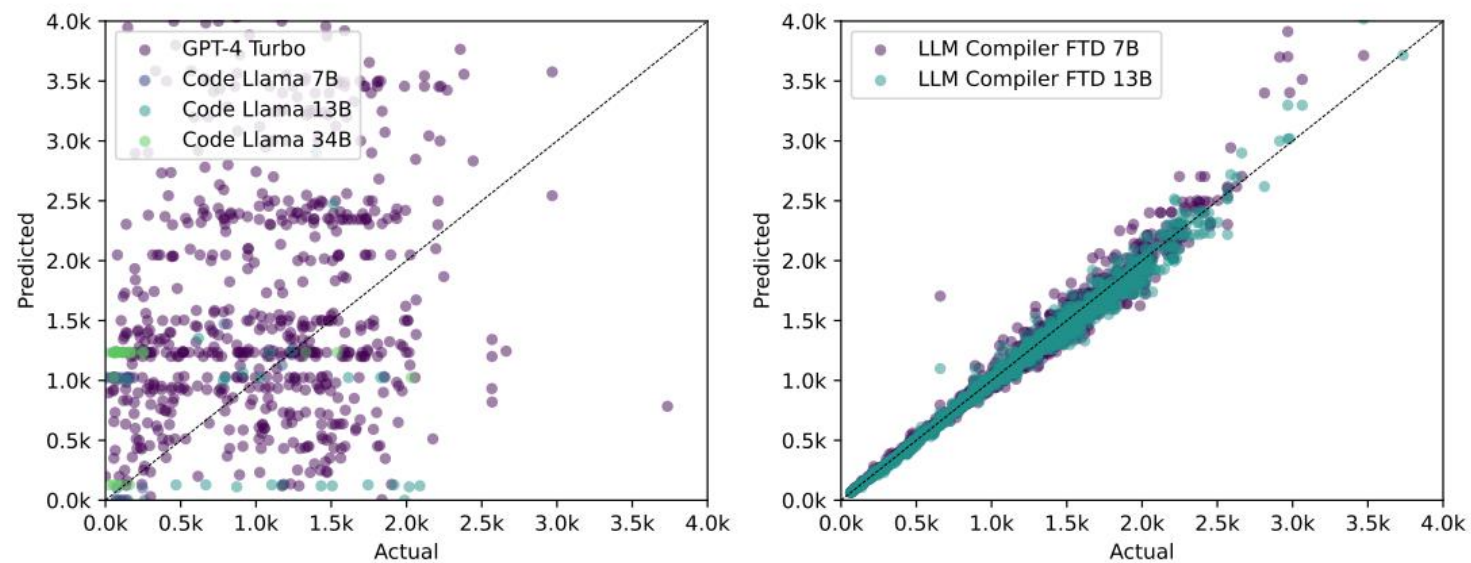
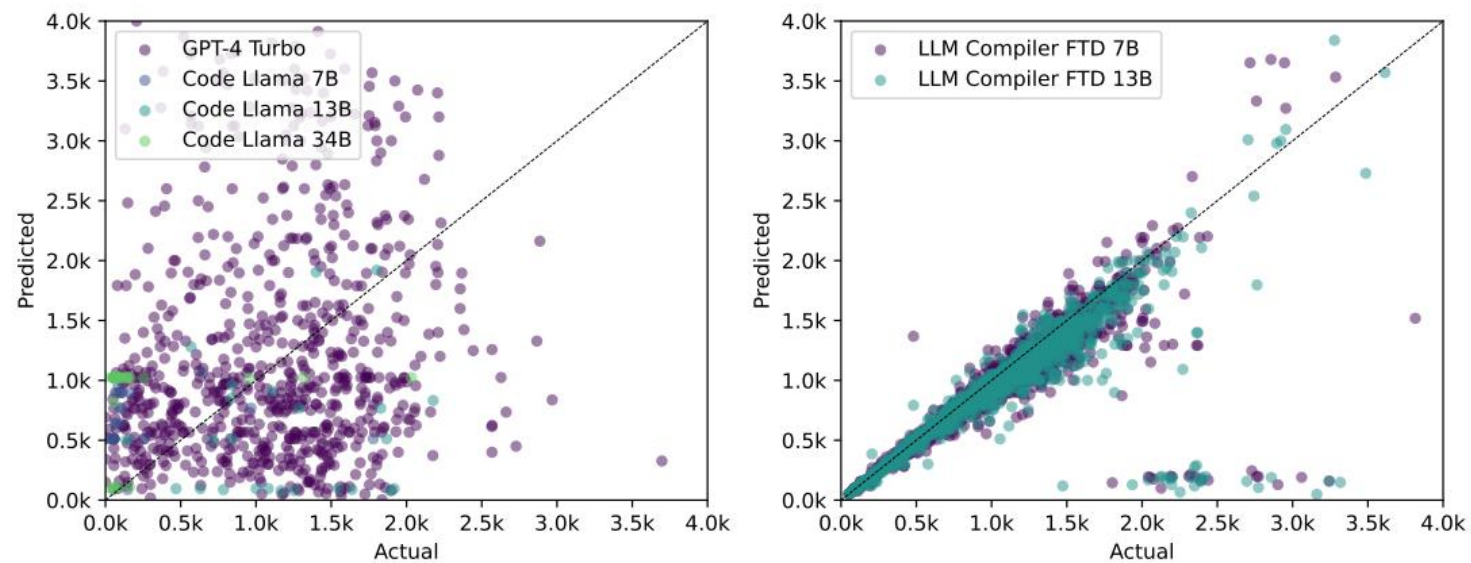


Figure 6: Improvement over -Oz for each of the benchmarks in MiBench.



(a) Unoptimized binary size



(b) Optimized binary size

Figure 7: Accuracy of models at predicting code size before and after optimization. LLM COMPILER FTD is most accurate at predicting code size before optimization than after optimization. CODE LLAMA and GPT-4 Turbo, shown left, display little correlation between predicted and actual values.

Disassembly Task

- Dataset: MiBench benchmark suite
- Method
 - Assembly Code (input)
 - LLVM IR (output)
- Models
 - GPT-4 Turbo
 - Code Llama Instruct

Table 5: Model performance at disassembling 2,015 assembly codes taken from MiBench. We use *Round trips* to evaluate the capabilities of models, by taking the IR generated by the models and attempting to lower it back to assembly. *Round trips* shows the number of disassembled IRs that can be lowered back, *Round trip BLEU* compares the round-tripped assemblies against the originals, and *Round trip exact match* is the proportion of round-tripped assemblies that are exact character-for-character matches with the input, indicating lossless round-trip from assembly up to IR and back down again.

	Size	Round trips	Round trip BLEU	Round trip exact match
LLM COMPILER FTD	7B	936	0.951	12.7%
	13B	905	0.960	13.8%
CODE LLAMA - INSTRUCT	7B	30	0.477	0.0%
	13B	53	0.615	0.0%
	34B	12	0.458	0.0%
GPT-4 Turbo (2024-04-09)	-	127	0.429	0.0%

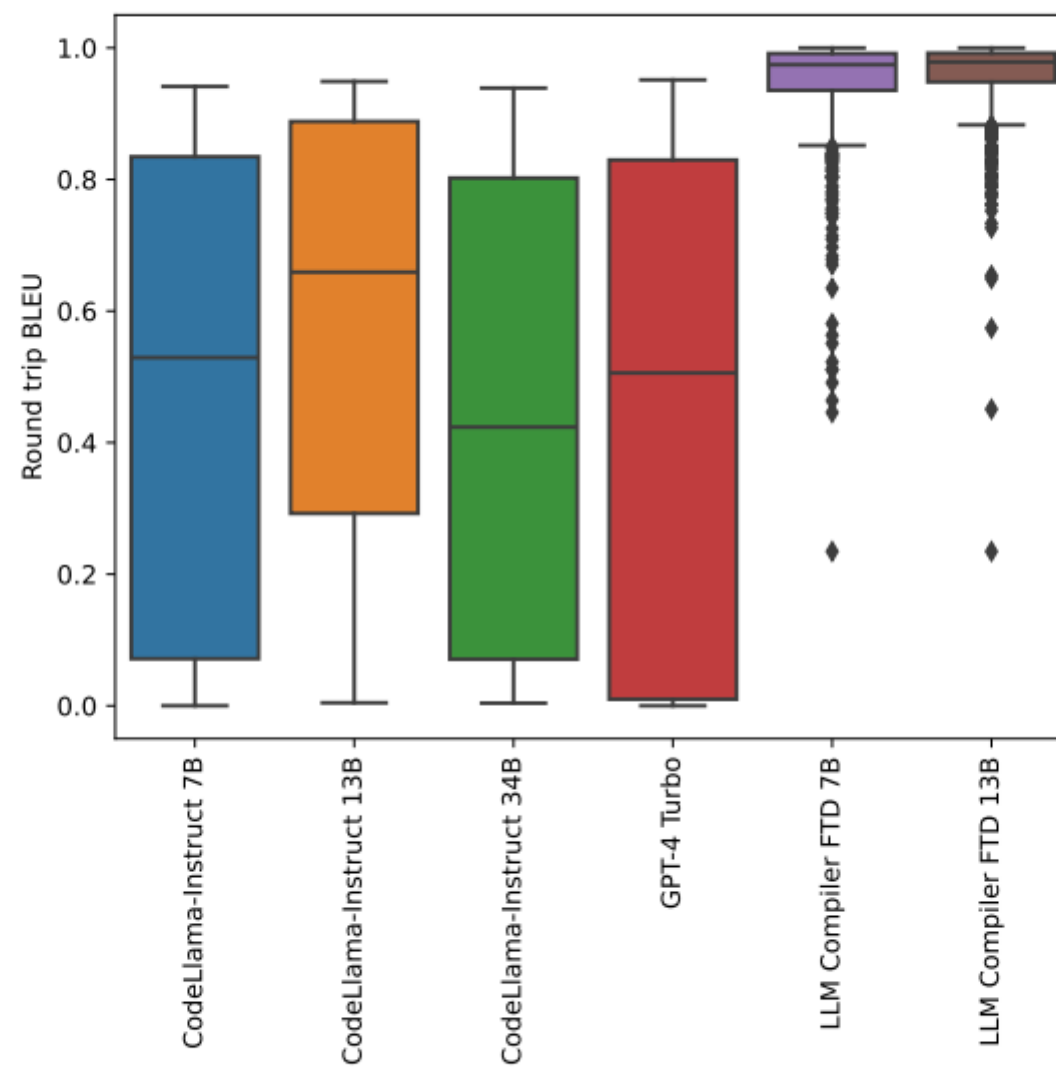


Figure 8: Distribution of round trip BLEU scores on the disassembly task.