CCS 2024, Salt Lake City, Utah

Distinguished Paper Award

ReSym: Harnessing LLMs to Recover Variable and Data Structure Symbols from Stripped Binaries

Danning Xie, Zhuo Zhang, Nan Jiang, Xiangzhe Xu, Lin Tan, Xiangyu Zhang

PURDUE UNIVERSITY

Background: Stripped Binary and Decompiled Code

Source Code

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 ushort len;
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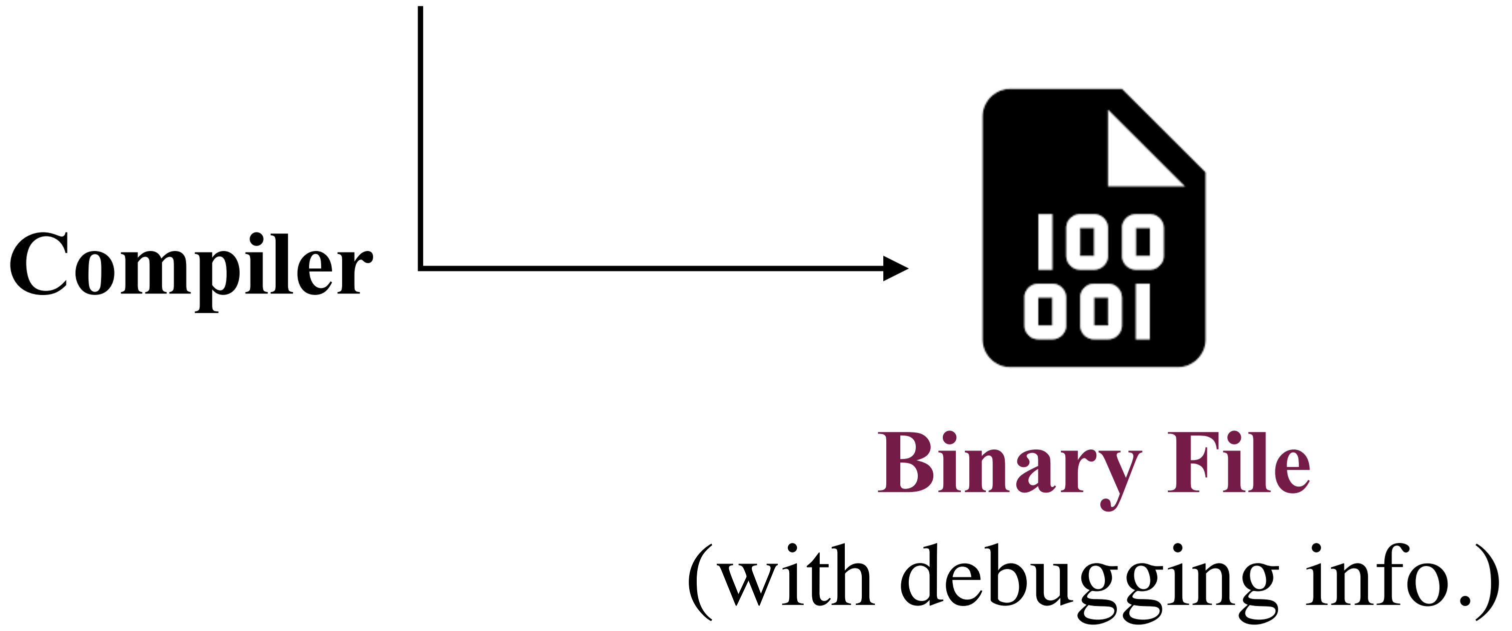

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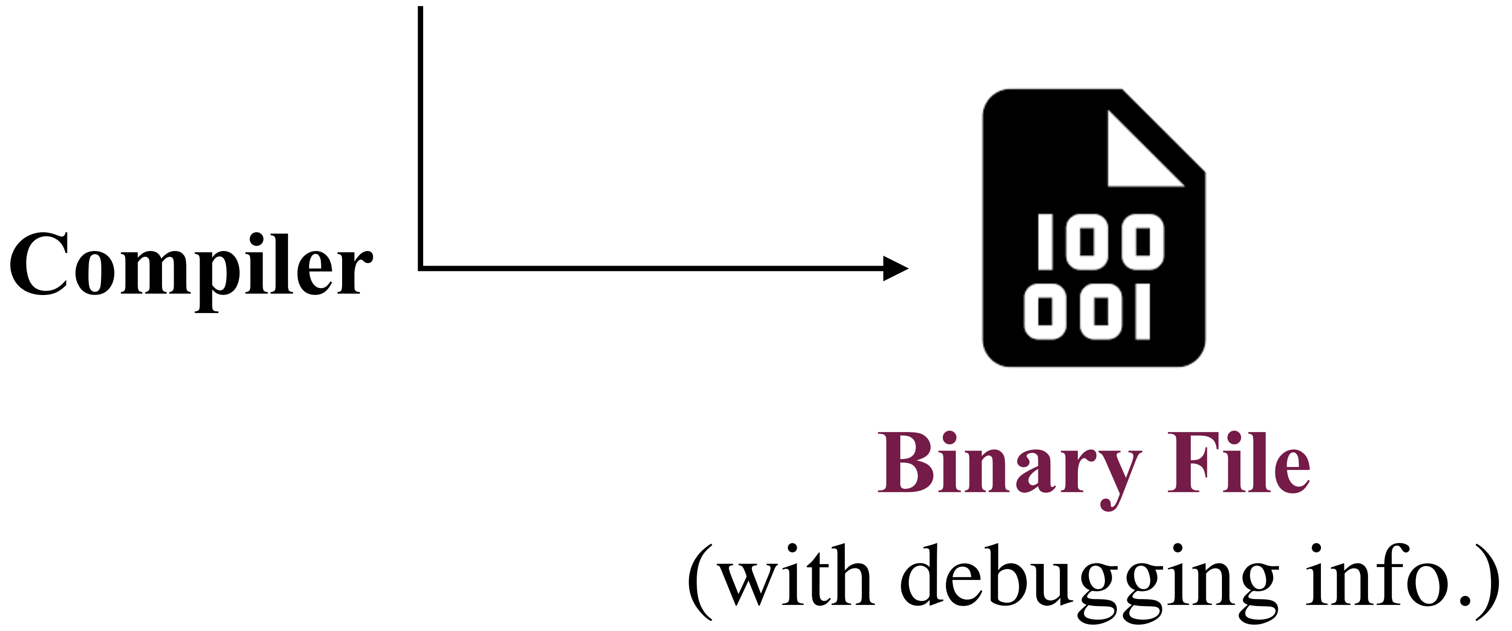

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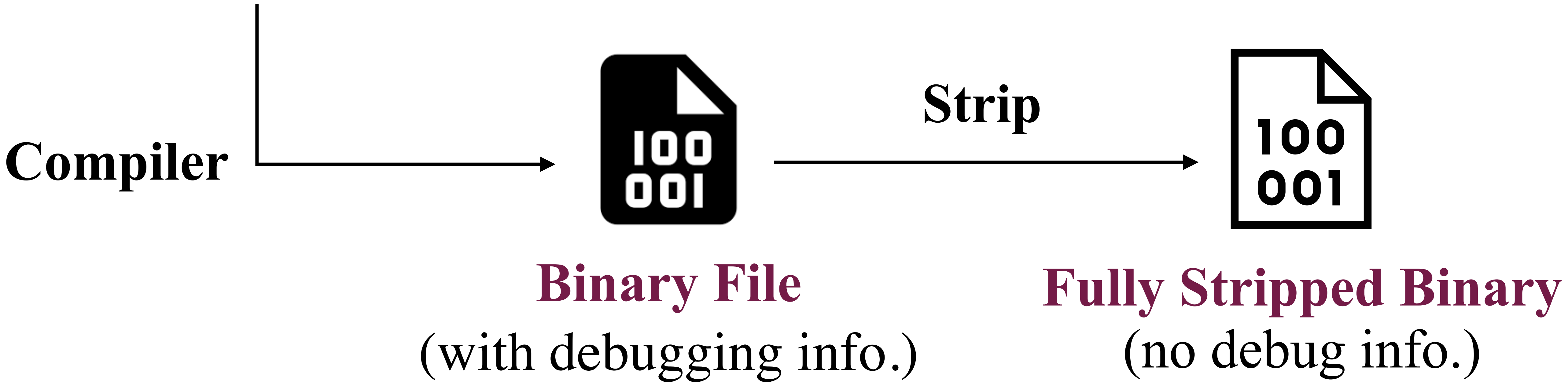

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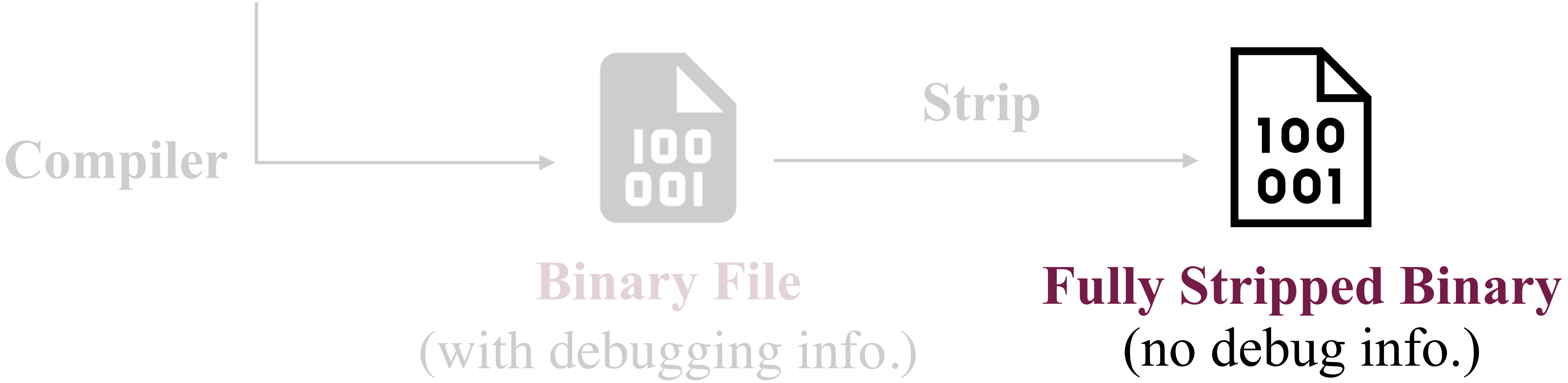

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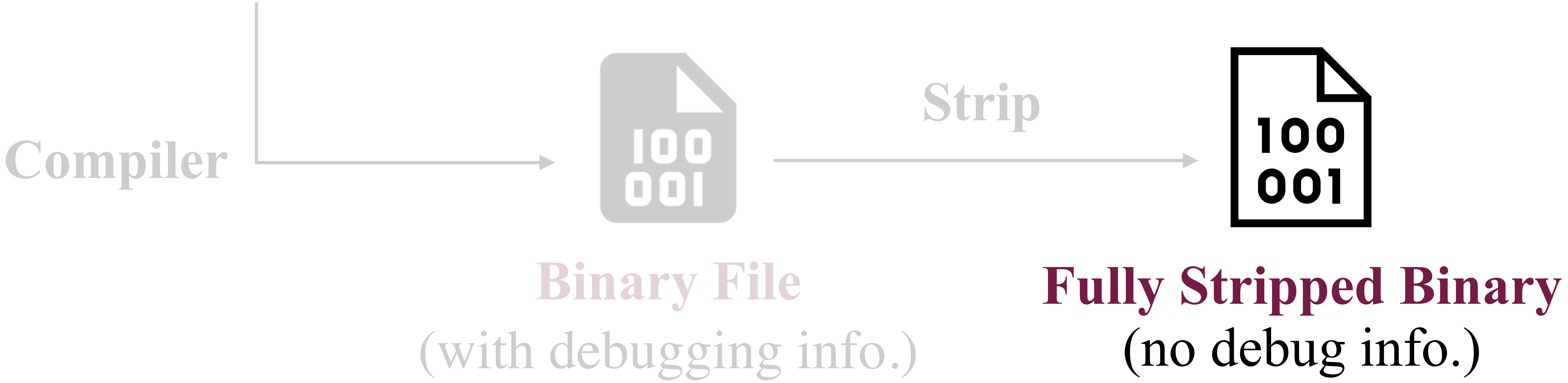

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Understanding stripped binaries is essential to ensure software security.

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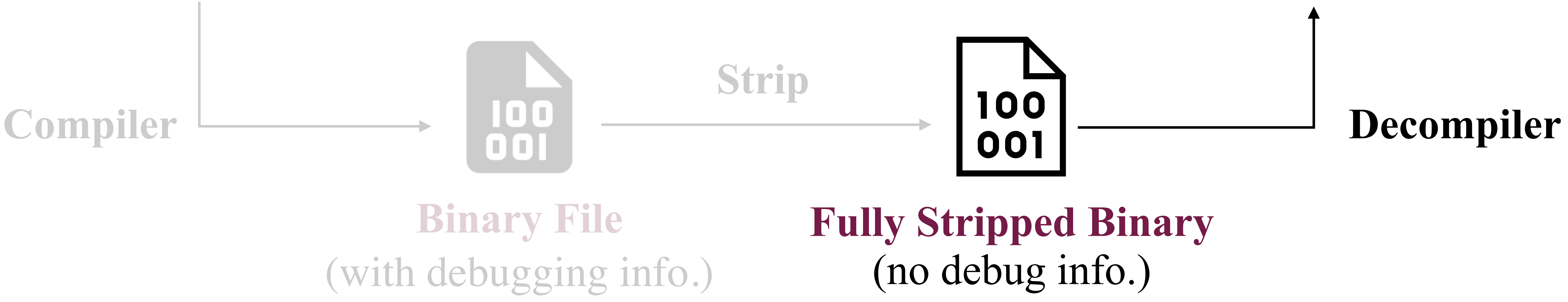

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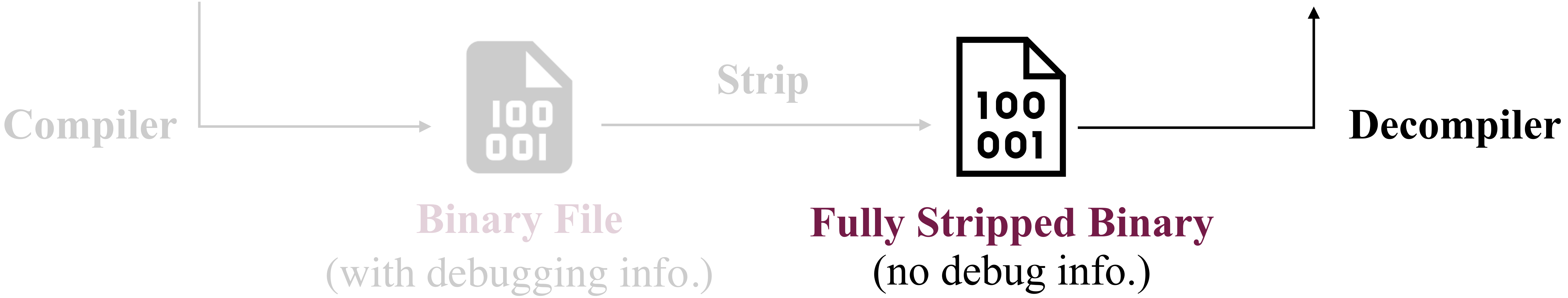

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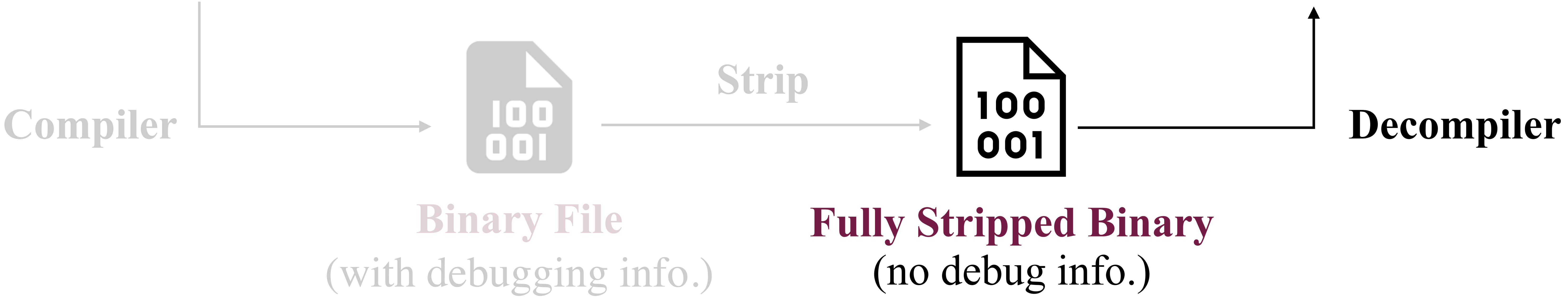

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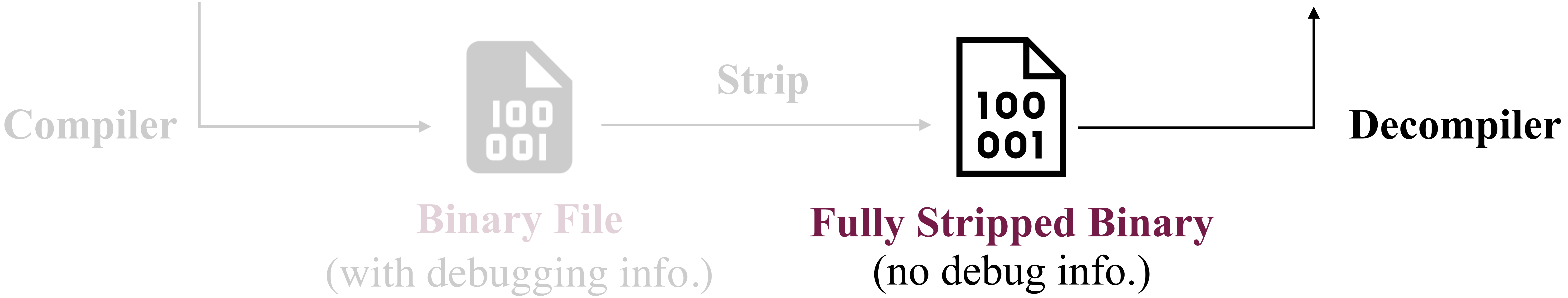

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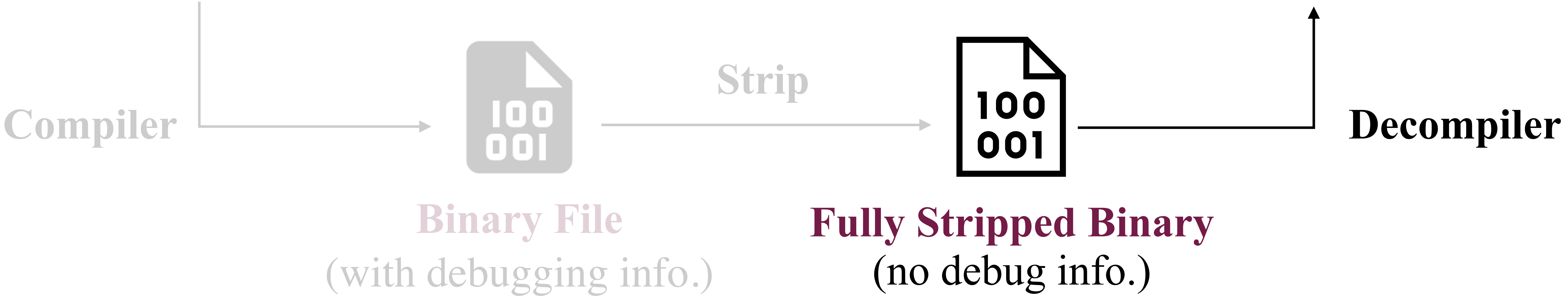

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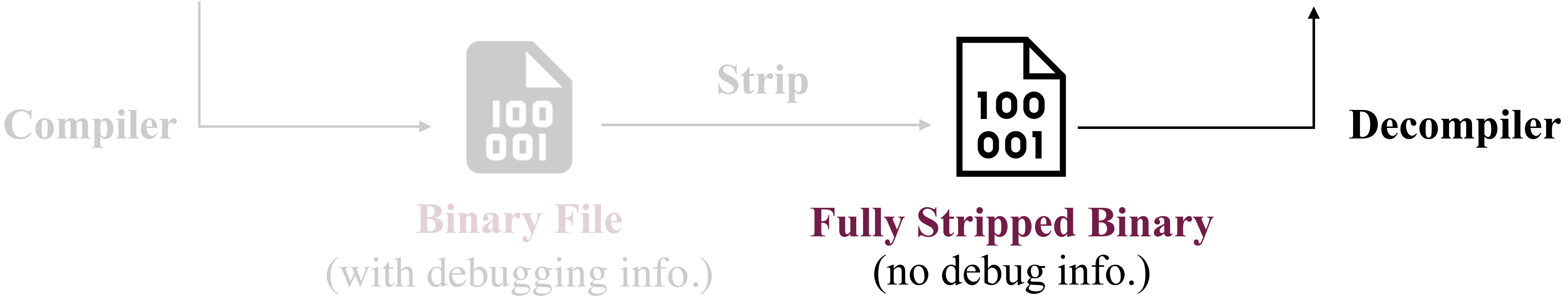

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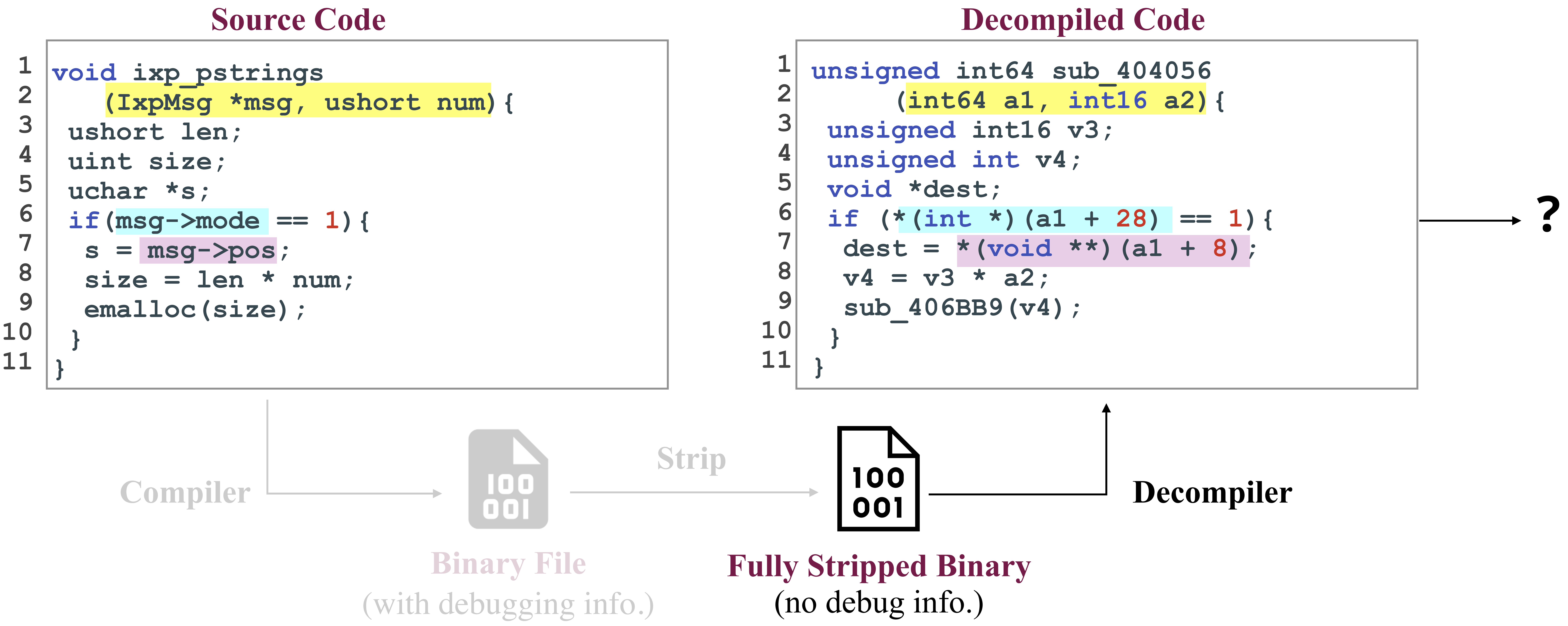

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Existing Techniques are Limited on Recovering User-defined Data Structures

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```
struct IxpMsg {
 char*     data;
 char*     pos;
 char*     end;
 _ixpuint size;
 _ixpuint mode;
};
```

Ground Truth

Existing Techniques are Limited on Recovering User-defined Data Structures

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```
struct sha256_ctx {
 uint32_t H[8];
 uint32_t total[2];
 uint32_t buflen;
 char buffer[128];
};
```

DIRTY

Uses a multi-classification model

```
struct struct0{
 int8*  s_0,
 int8*  s_1,
 int8*  s_2,
 int64  s_3,
 int64  s_4
};
```

OSPREY

Only recovers layout

Opportunities: LLMs' Power of Code Comprehension

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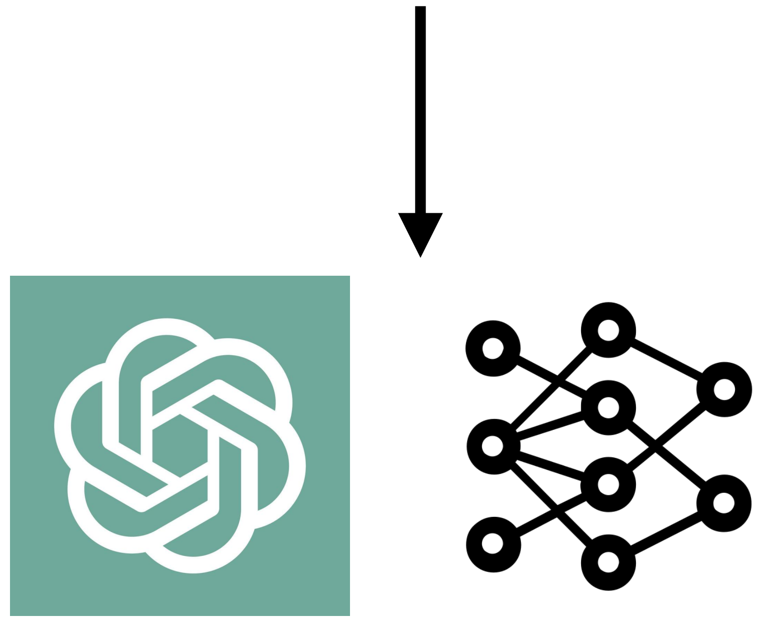

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void process
  (state *s, unsigned short n){
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Challenges:

- A **general-purpose LLM** (e.g., ChatGPT) **struggles** to produce readable decompiled code.
- LLMs' direct outputs may have **incorrect semantics**.
- Accurate recovery requires a **global view**, while LLMs have token limits.

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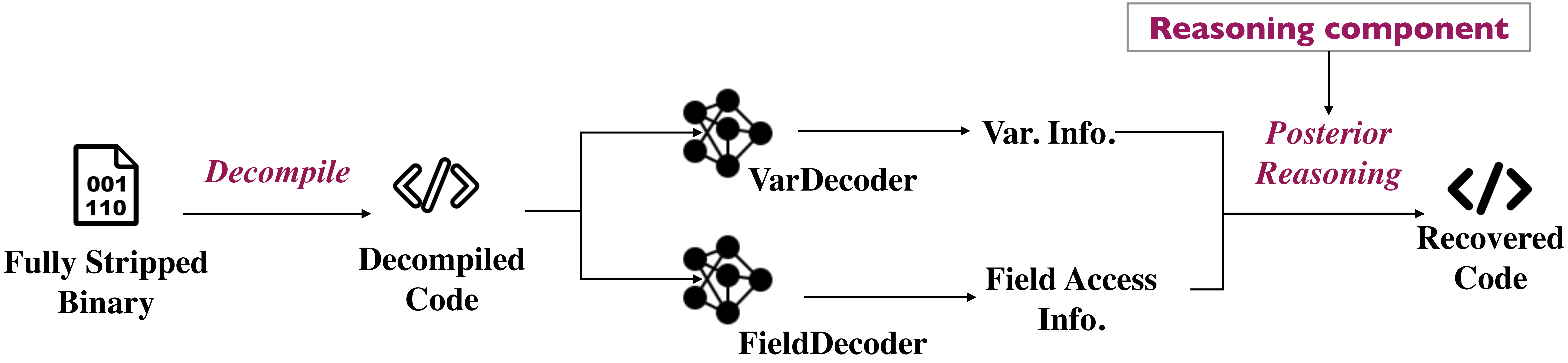
① **Break** the task into smaller manageable subtasks

② Focus on one piece at a time and then **aggregate** insights from multiple code snippets

ReSym Pipeline

Key idea: Break and Aggregate



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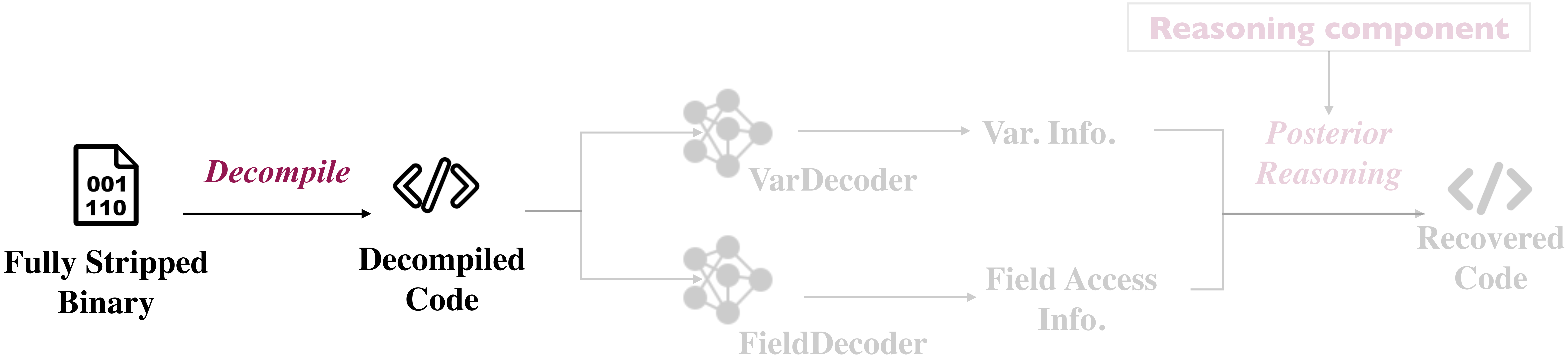

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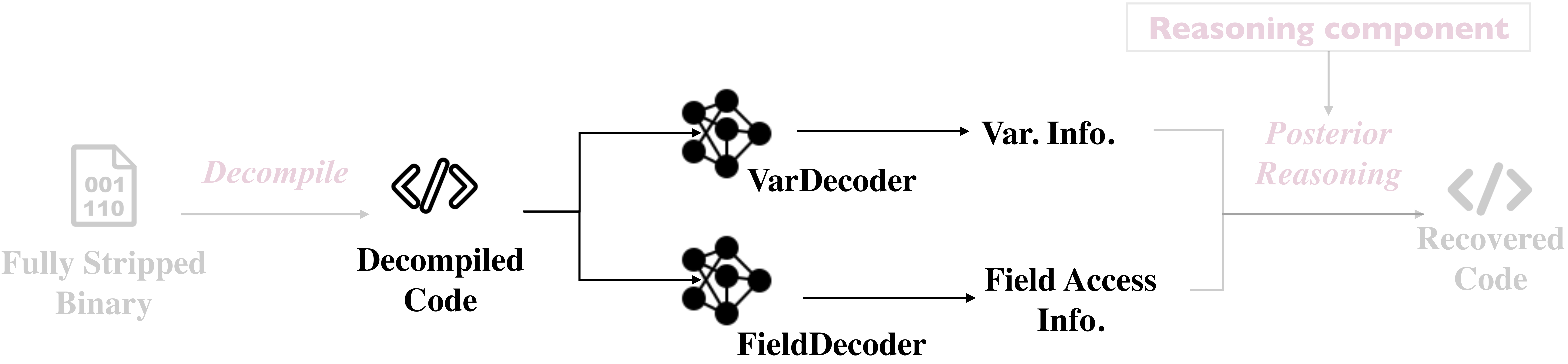

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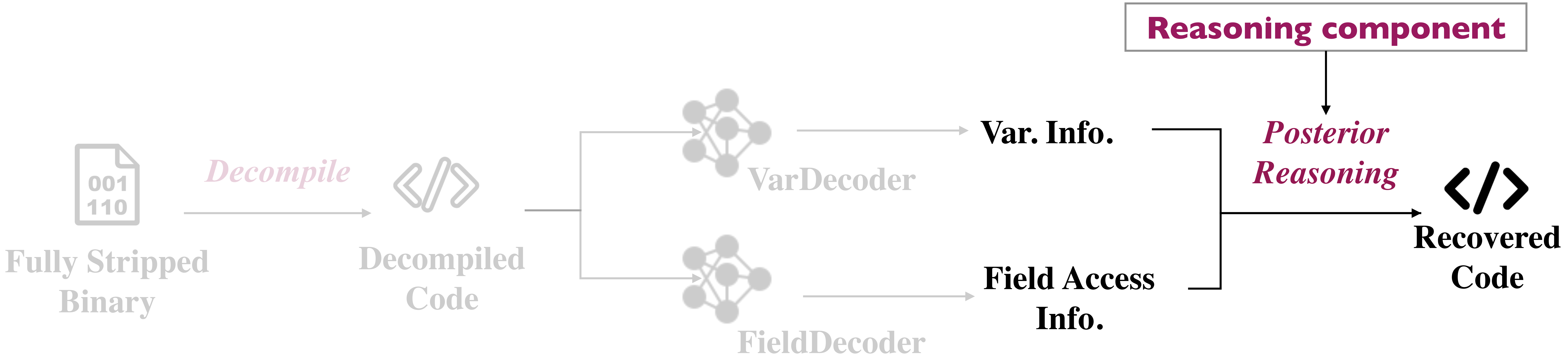

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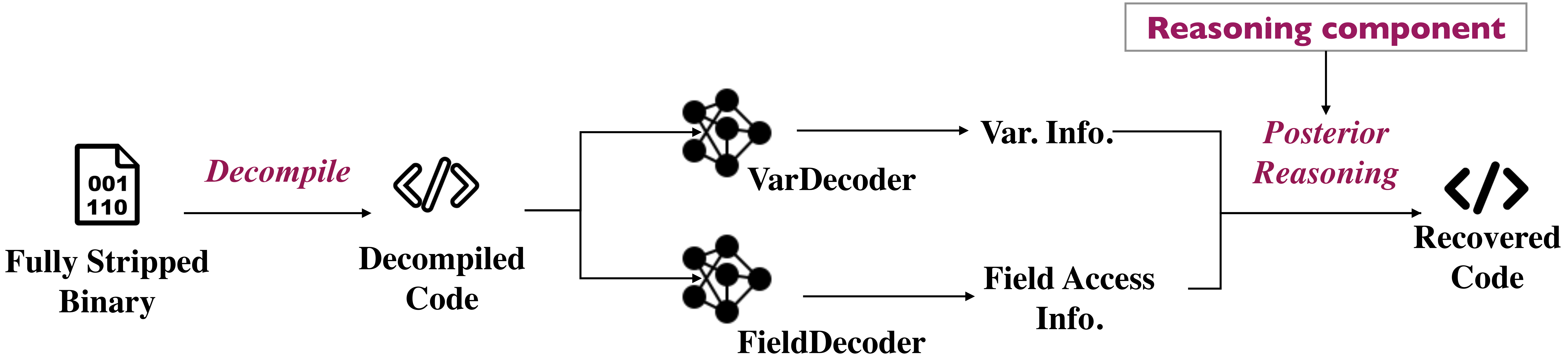

VarDecoder: Recover Variable Information

Decompiled Code

```
unsigned int64 sub_404056
     (int64 a1, int16 a2){
 unsigned int16 v3;
 unsigned int v4;
 void *dest;
 if (*(int *)(a1 + 28) == 1){
  dest = *(void **)(a1 + 8);
  v4 = v3 * a2;
  sub_406BB9(v4);
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VarDecoder

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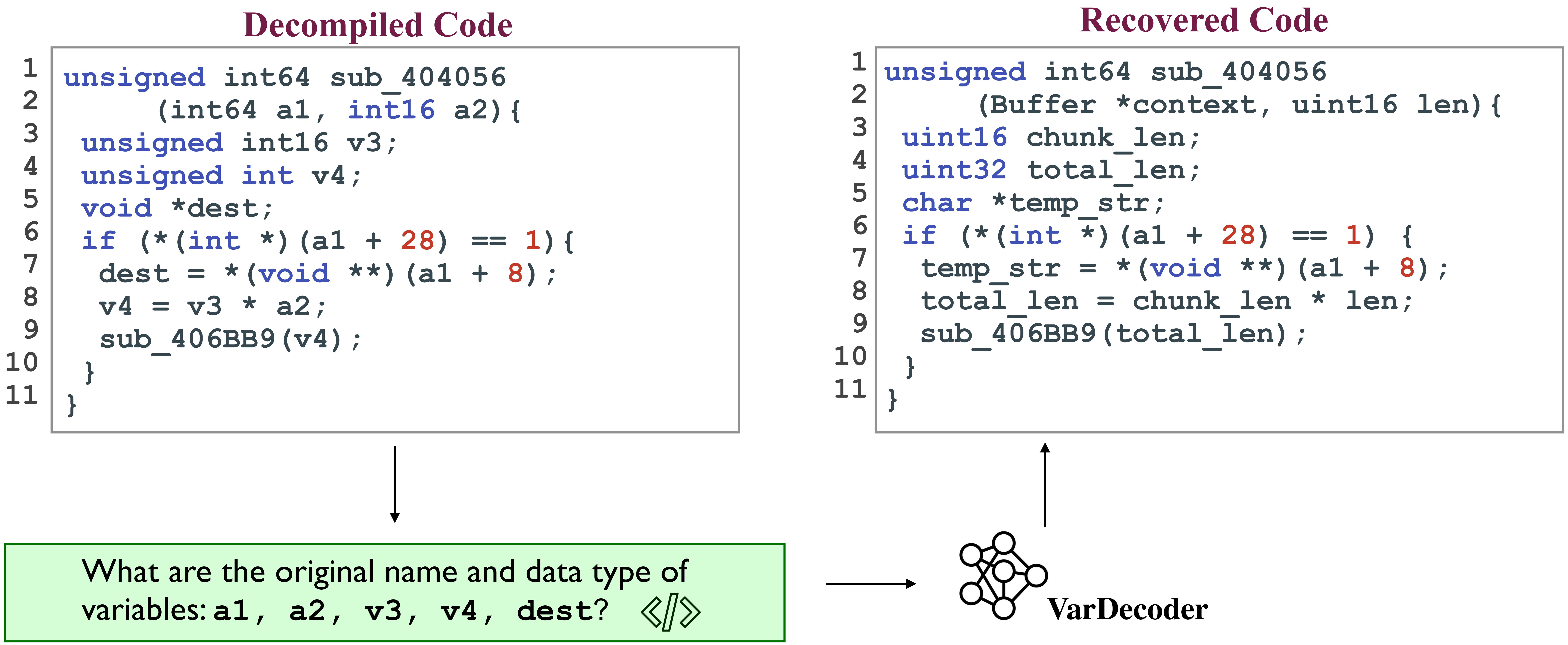

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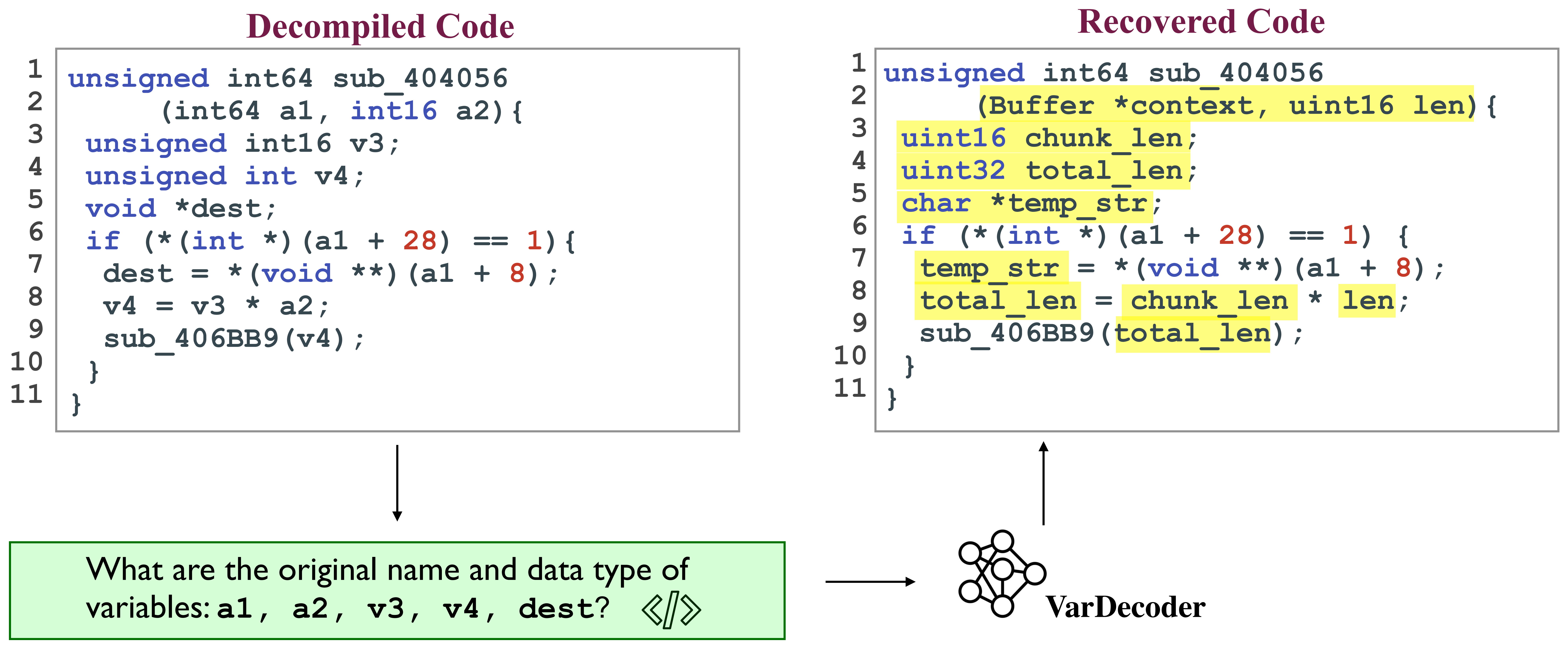

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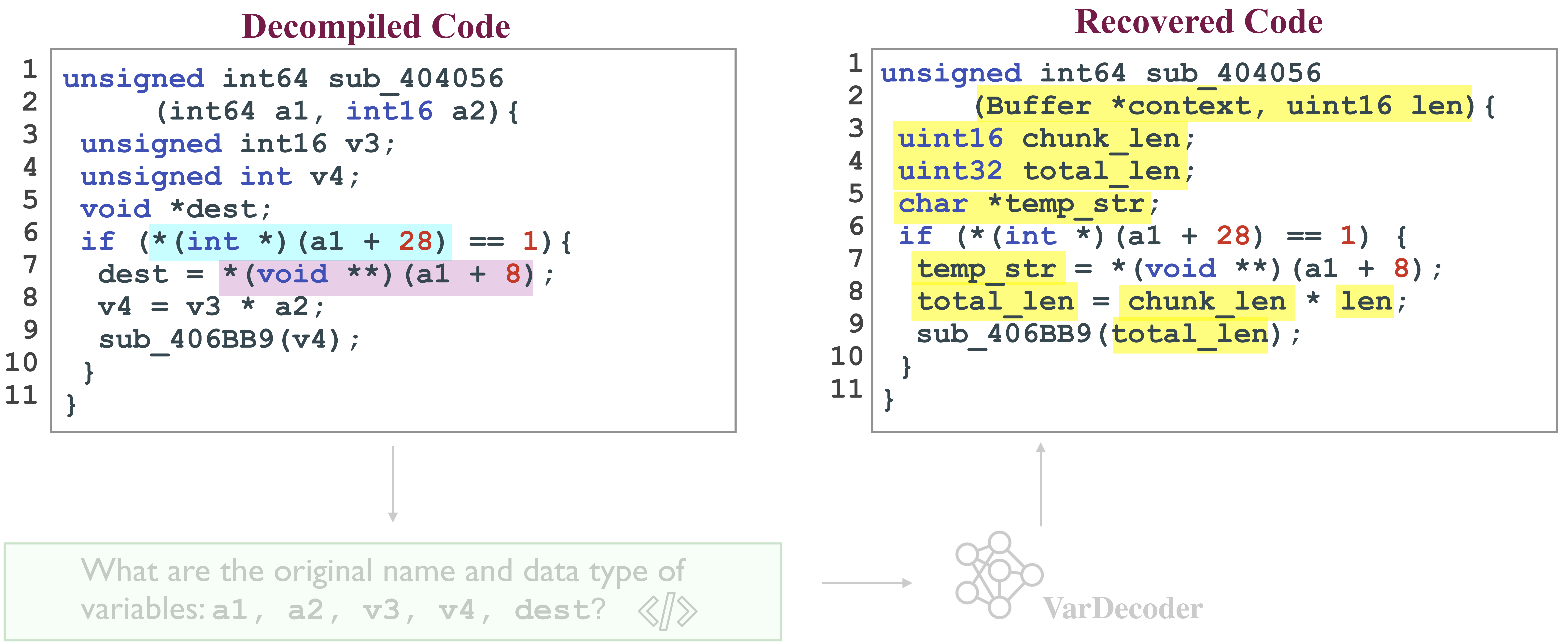

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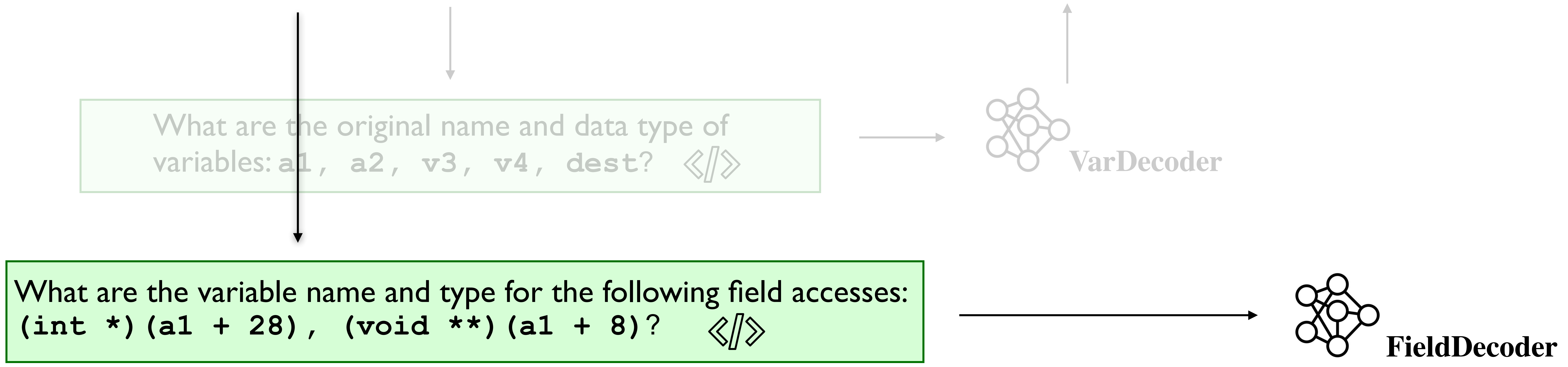

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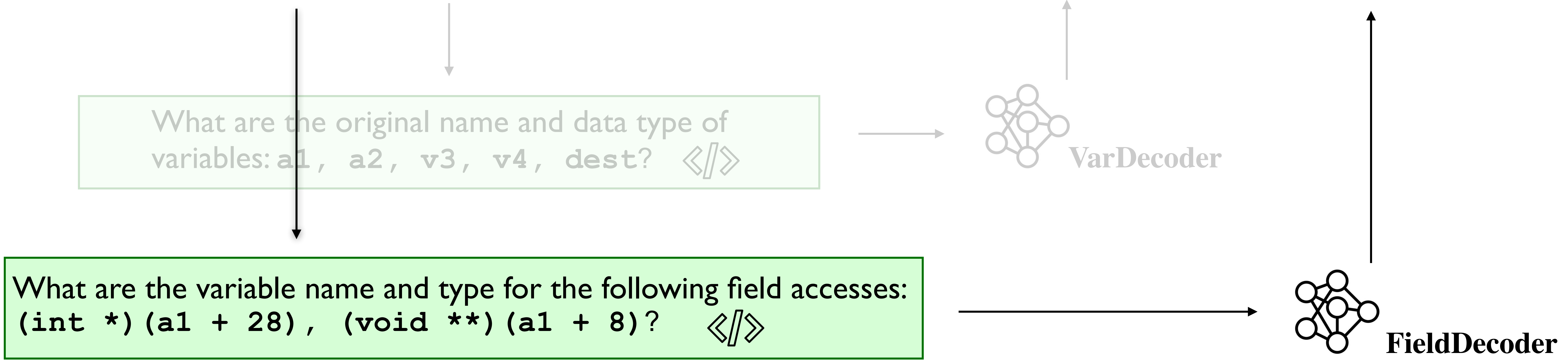
  v4 = v3 * a2;
  sub_406BB9(v4);
 }
}
```

Recovered Code

```
unsigned int64 sub_404056
     (Buffer *context, uint16 len){
 uint16 chunk_len;
 uint32 total_len;
 char *temp_str;
 if (context->type == 1) {
  temp_str = context->pos;
  total_len = chunk_len * len;
  sub_406BB9(total_len);
 }
}
```



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Posterior Reasoning:

Aggregating Field Access from Multiple Functions

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 }
}
```

Recovered Data Structure

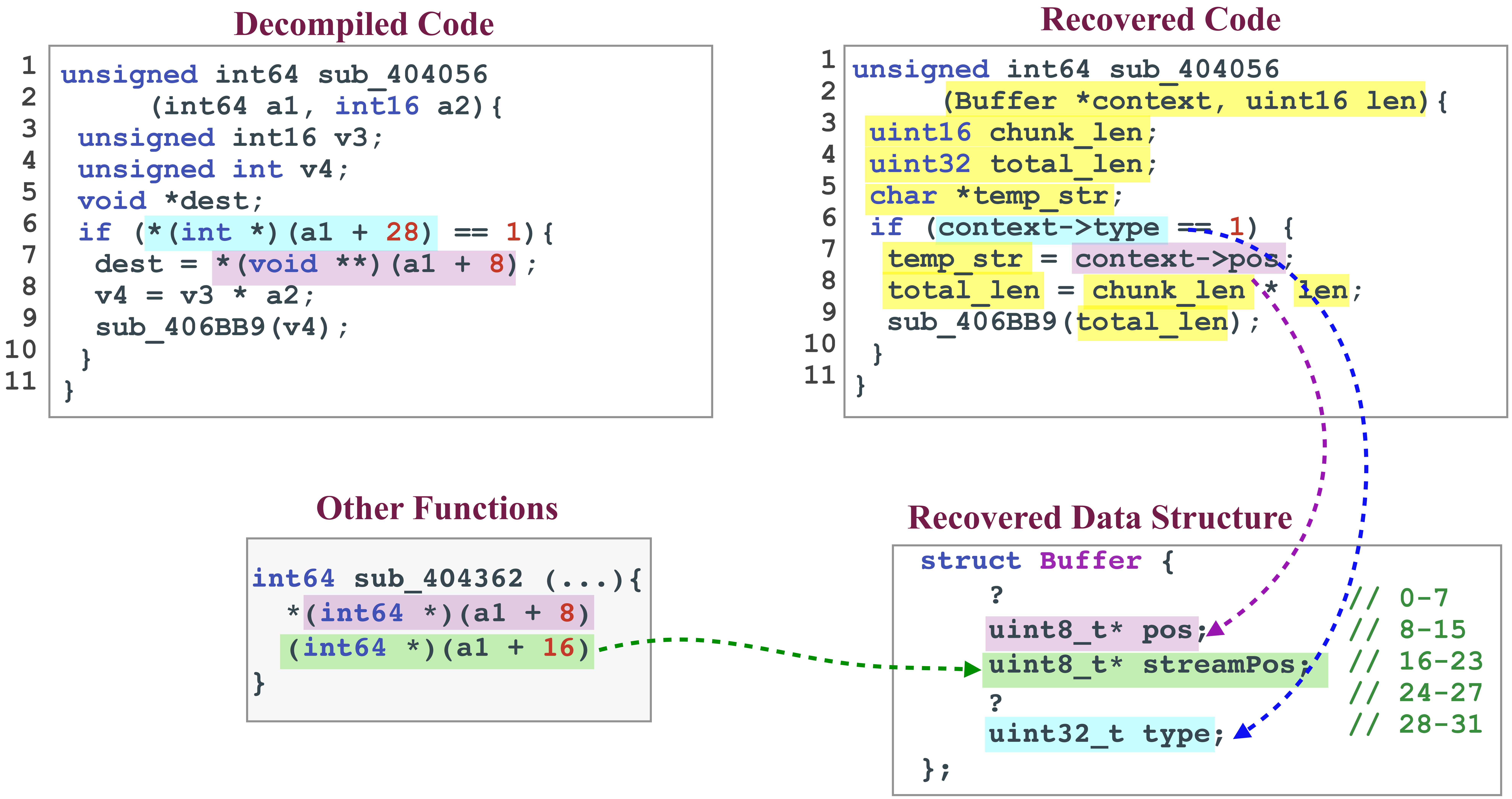
```
struct Buffer {
    ?                          // 0-7
    uint8_t* pos;              // 8-15

    ?                          ?

    uint32_t type;             // 28-31
};
```

Posterior Reasoning:

Aggregating Field Access from Multiple Functions



Decompiled Code

```
unsigned int64 sub_404056
      (int64 a1, int16 a2){
 unsigned int16 v3;
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 if (context->type == 1) {
  temp_str = context->pos;
  total_len = chunk_len * len;
  sub_406BB9(total_len);
 }
}
```

Other Functions

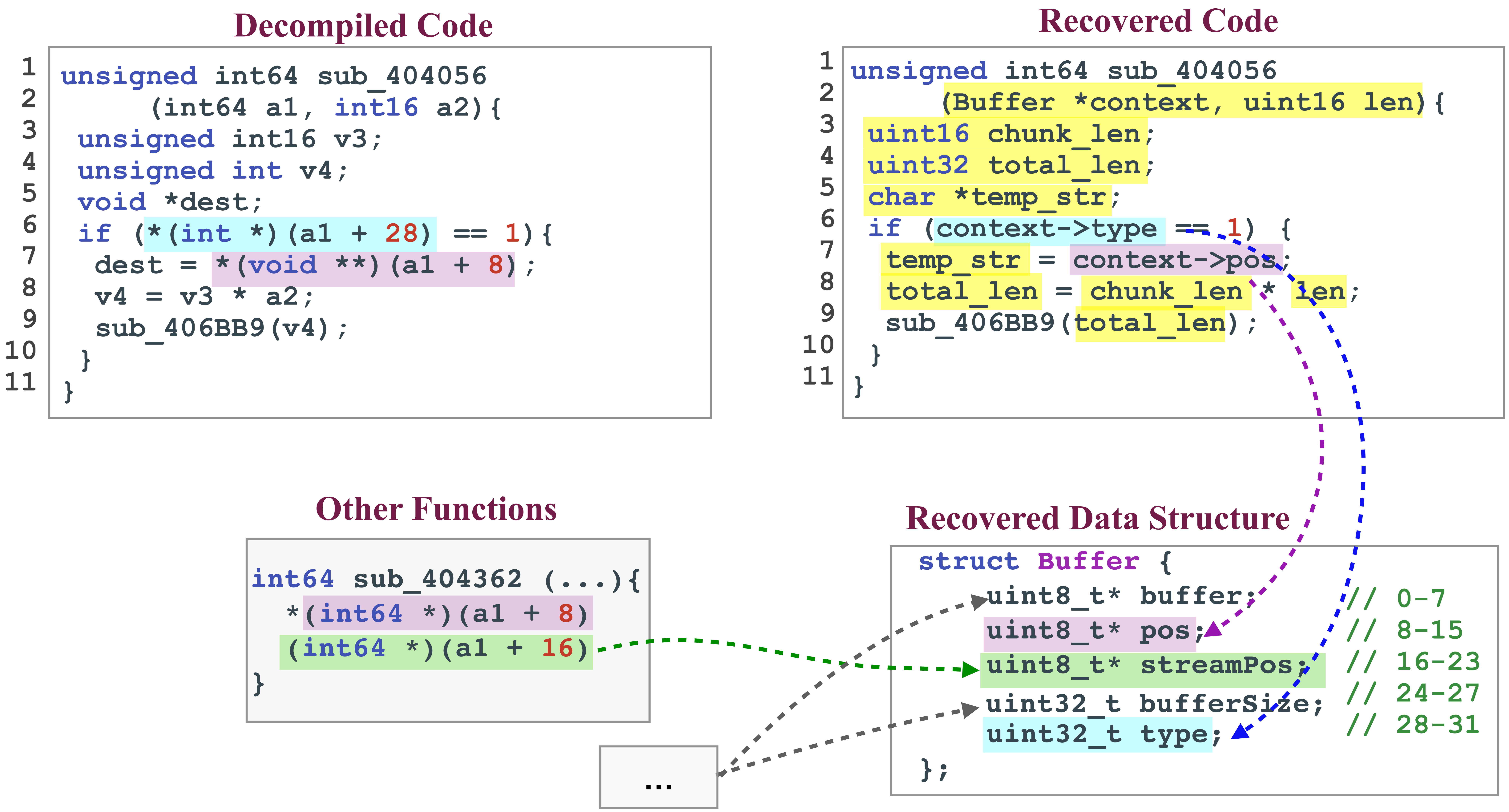
```
int64 sub_404362 (...){
  *(int64 *)(a1 + 8)
  (int64 *)(a1 + 16)
}
```

Recovered Data Structure

```
struct Buffer {
      ?                       // 0-7
      uint8_t* pos;           // 8-15
      uint8_t* streamPos;     // 16-23
      ?                       // 24-27
      uint32_t type;          // 28-31
};
```

Posterior Reasoning:

Aggregating Field Access from Multiple Functions



Decompiled Code

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```

Recovered Code

```
unsigned int64 sub_404056
     (Buffer *context, uint16 len){
 uint16 chunk_len;
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 if (context->type == 1) {
  temp_str = context->pos;
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  sub_406BB9(total_len);
 }
}
```

Other Functions

```
int64 sub_404362 (...){
  *(int64 *)(a1 + 8)
  (int64 *)(a1 + 16)
}
```

```
...
```

Recovered Data Structure

```
 struct Buffer {
     uint8_t* buffer;      // 0-7
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     uint32_t bufferSize;  // 24-27
     uint32_t type;        // 28-31
 };
```

Existing Techniques are Limited on Recovering User-defined Data Structures

Source Code

```
void ixp_pstrings
   (IxpMsg *msg, ushort num){
 ushort len;
 uint size;
 uchar *s;
 if(msg->mode == 1){
  s = msg->pos;
  size = len * num;
  emalloc(size);
 }
}
```

Decompiled Code

```
unsigned int64 sub_404056
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  v4 = v3 * a2;
  sub_406BB9(v4);
 }
}
```

```
struct IxpMsg {
 char*     data;
 char*     pos;
 char*     end;
 _ixpuint size;
 _ixpuint mode;
};
```

Ground Truth

```
struct sha256_ctx {
 uint32_t H[8];
 uint32_t total[2];
 uint32_t buflen;
 char buffer[128];
};
```

DIRTY

Uses a multi-classification model

```
struct struct0{
 int8*   s_0,
 int8*   s_1,
 int8*   s_2,
 int64   s_3,
 int64   s_4
};
```

OSPREY

Only recovers layout

Existing Techniques are Limited on Recovering User-defined Data Structures

Source Code

```
void ixp_pstrings
   (IxpMsg *msg, ushort num){
 ushort len;
 uint size;
 uchar *s;
 if(msg->mode == 1){
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OSPREY

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```
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 uint8_t* buffer;
 uint8_t* pos;
 uint8_t* streamPos;
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```

ReSym

Experimental Setup

- **3,058** C/C++ real-world projects collected from GitHub
- **16,217** binary files
  - average size: **116 KB**; maximum size: **8.9 MB**
- Split train/test set **by project** with a ratio of 0.95
- Fine-tune two **StarCoder 3B** models for VarDecoder and FieldDecoder

Research Questions

- How good is ReSym at recovering variable names and types?
- How good is ReSym at recovering user-defined data structures?

Evaluation: Name and Type Recovery

Perfect match accuracy (%)

Method	Overall	
	name	type
ReSym	56.7 8.0↑	60.7 4.9↑
DIRTY	48.7	55.8

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ReSym is effective in recovering variable names and types.

ReSym outperforms DIRTY by 4.9 — **8.0%**.

Evaluation: User-Defined Data Structure Recovery

Method	**Struct Layout**			**Struct Annotation (Accuracy)**		
	Precision	Recall	F1	Struct Type	Field Name	Field Type
ReSym	81.9	34.6	48.6	44.4	14.4	15.5

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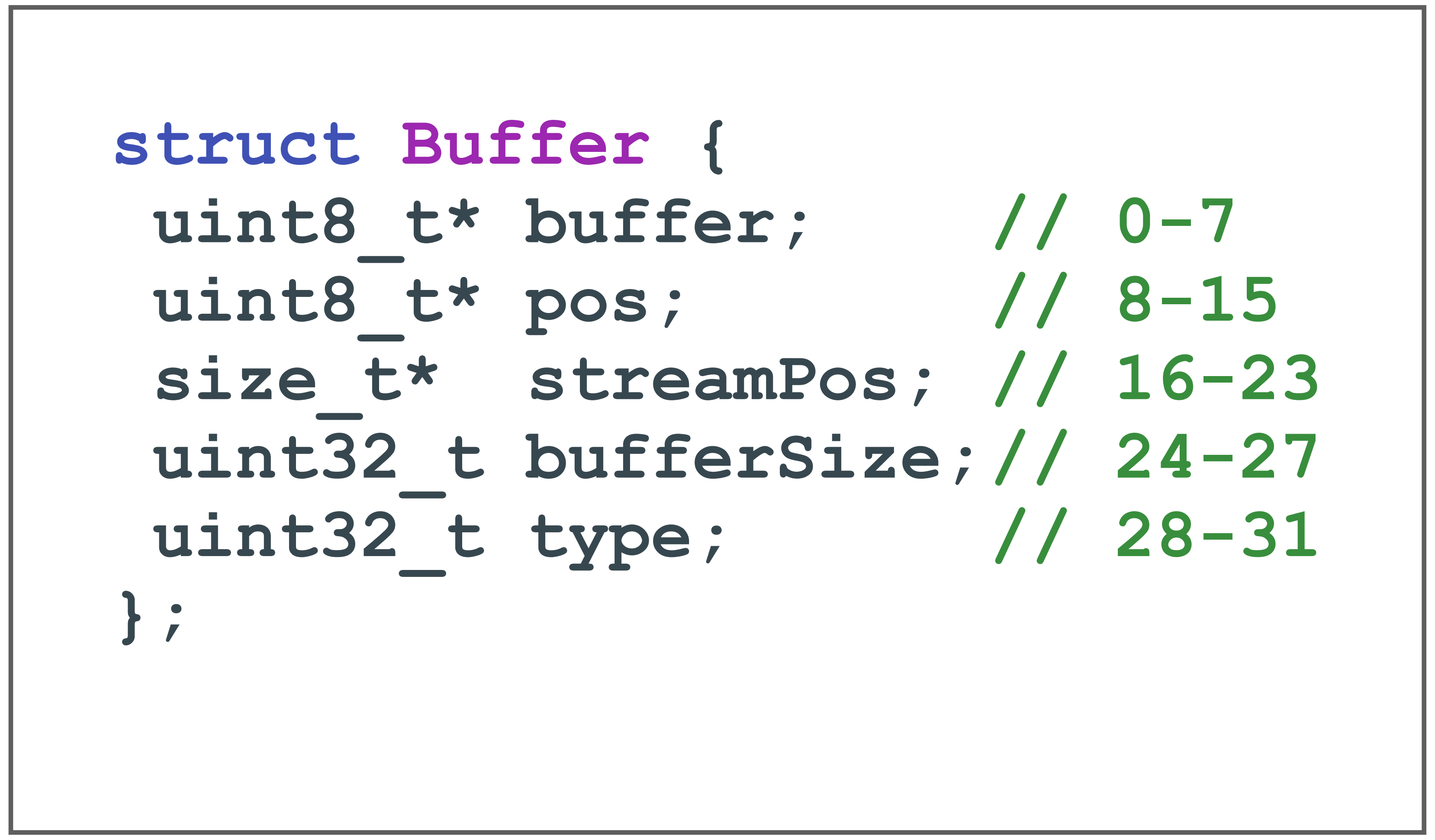

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predicted offsets and sizes

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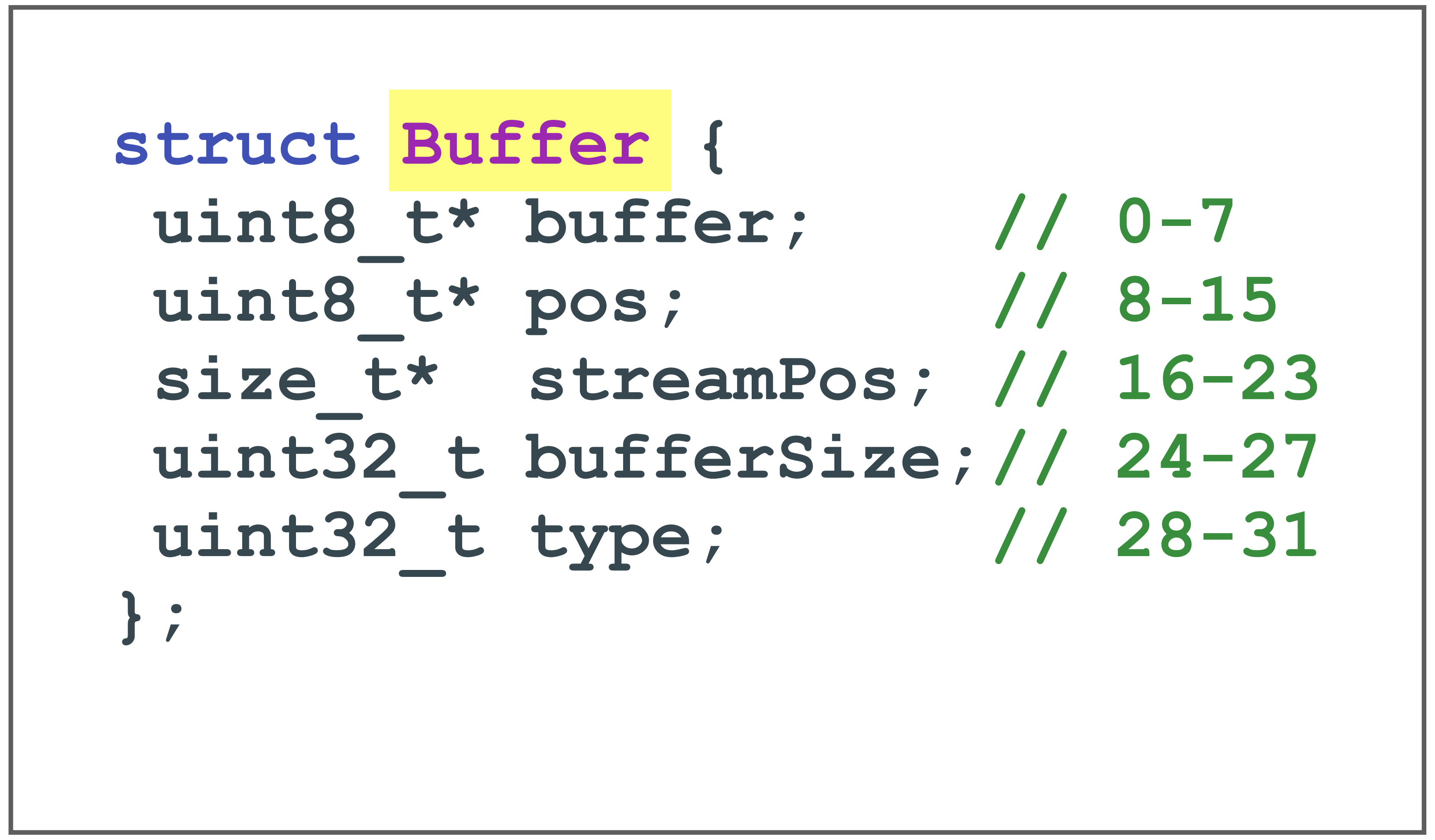

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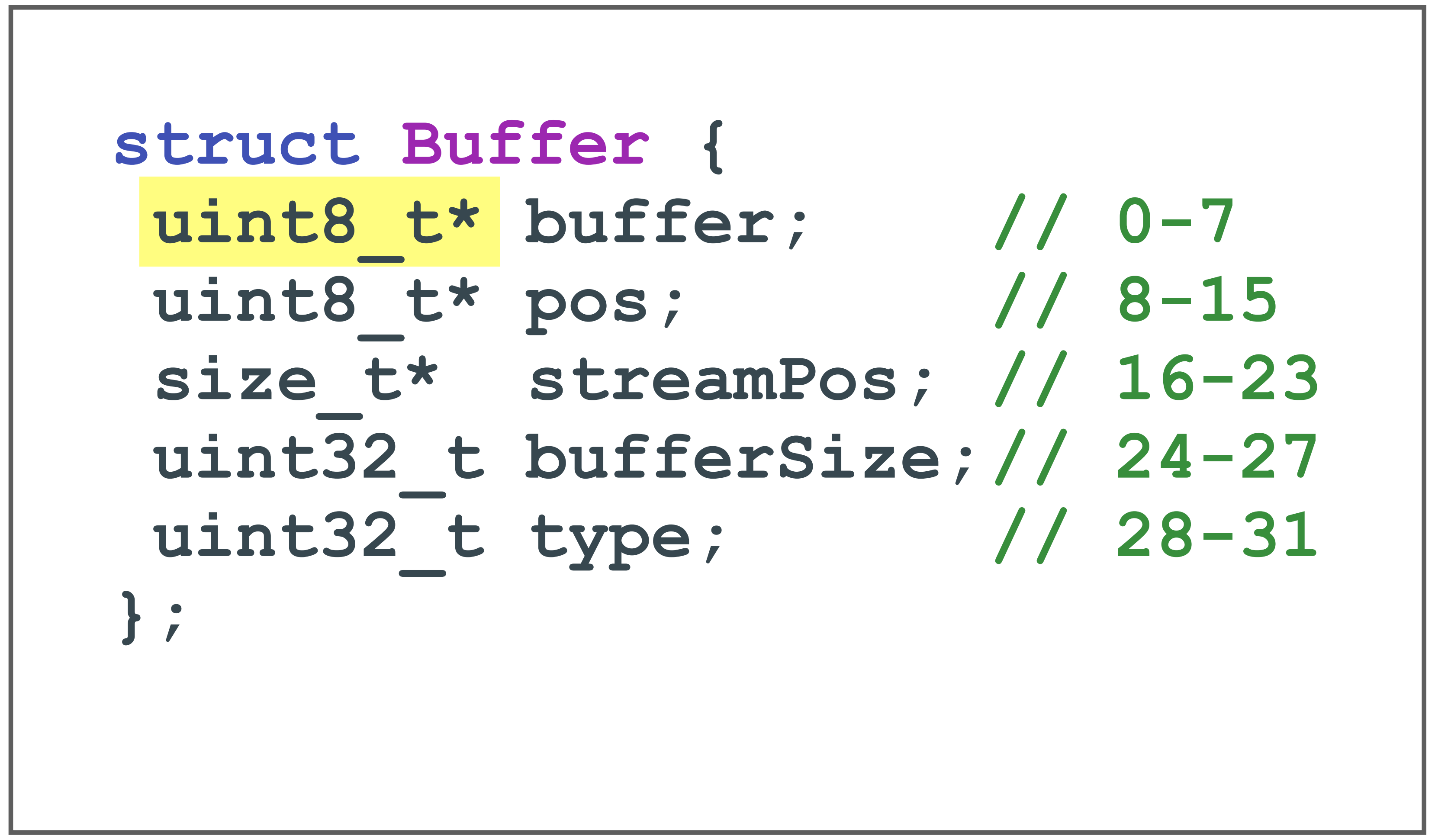

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ReSym without posterior reasoning

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ReSym without posterior reasoning

Posterior Reasoning is effective and improves the F1 score by 6.2%.

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ReSym's lower recall:

1. Discarding functions due to token limit
2. Data-flow analysis is inherently undecidable

Evaluation: User-Defined Data Structure Recovery

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ReSym achieves the highest F1 score and accurately recovers structure annotation.

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ReSym achieves the highest F1 score and accurately recovers structure annotation.

ReSym analyzes each binary file in 3.4s, while OSPREY takes 528.24s.

Conclusions

- Propose a prototype, **ReSym**, that harnesses LLMs to effectively recover variable and data structure symbols from stripped binaries.
- **Divide** the difficult symbol recovery problem into two manageable sub-problems.
- Develop a rigorous reasoning component to **aggregate** and cross-check local results, enabling the recovery of **comprehensive data structures**.
- ReSym **outperforms** state-of-the-art techniques, DIRTY and OSPREY.
- Build a **large-scale public dataset** of C/C++ projects containing binaries annotated with corresponding symbols, together with the automatic annotation pipeline, to facilitate future research.