OSPREY: Recovery of Variable and Data Structure via Probabilistic Analysis for Stripped Binary

Zhuo Zhang, Yapeng Ye, Wei You, Guanhong Tao, Wen-chuan Lee, Yonghwi Kwon, Yousra Aafer, Xiangyu Zhang

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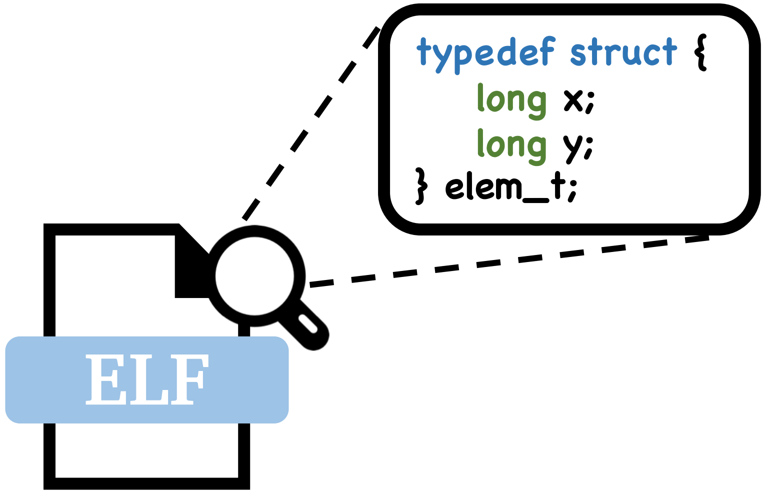
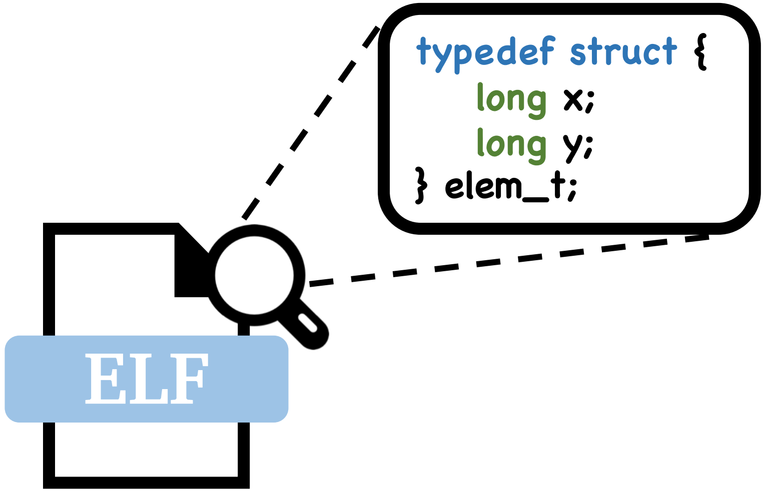
UNIVERSITY of VIRGINIA
UNIVERSITY OF WATERLOO



Variable and Data Structure Recovery

Bug Detection



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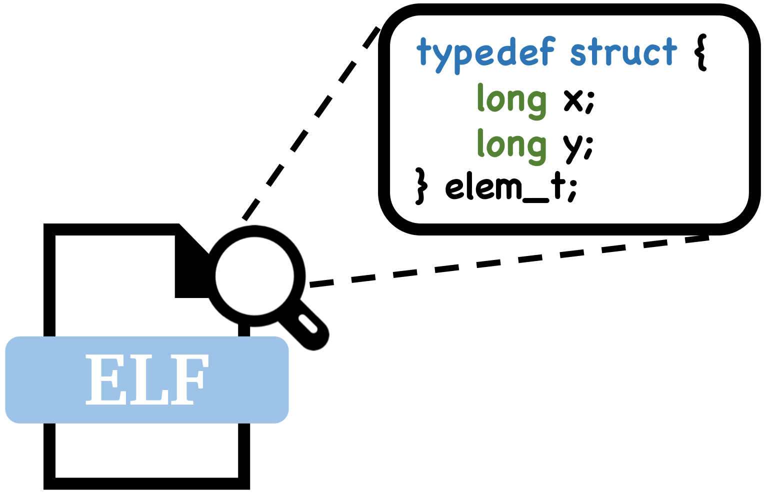

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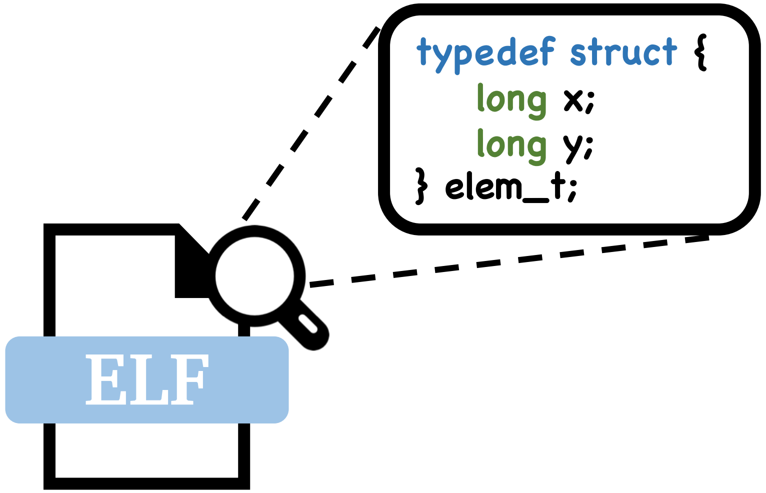
Malware Analysis



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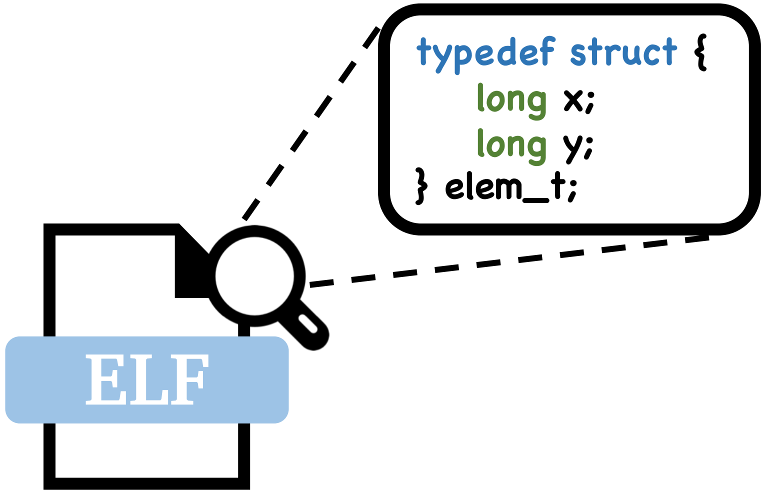
Automatic Exploit Generation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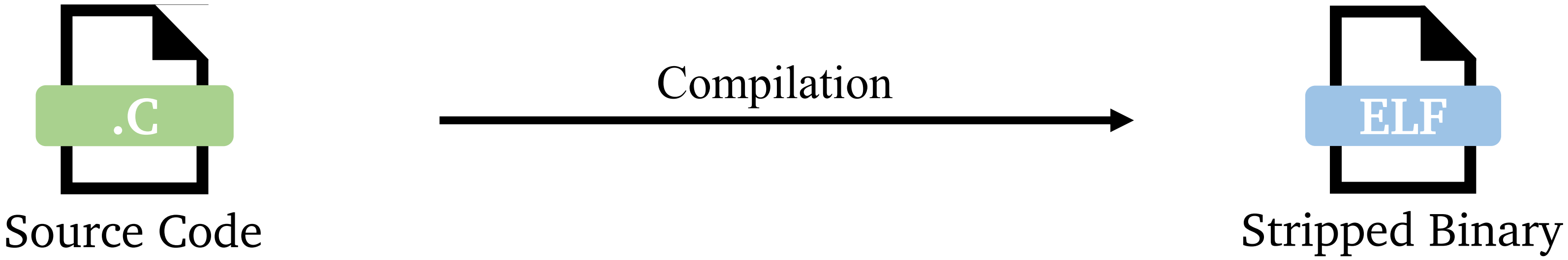
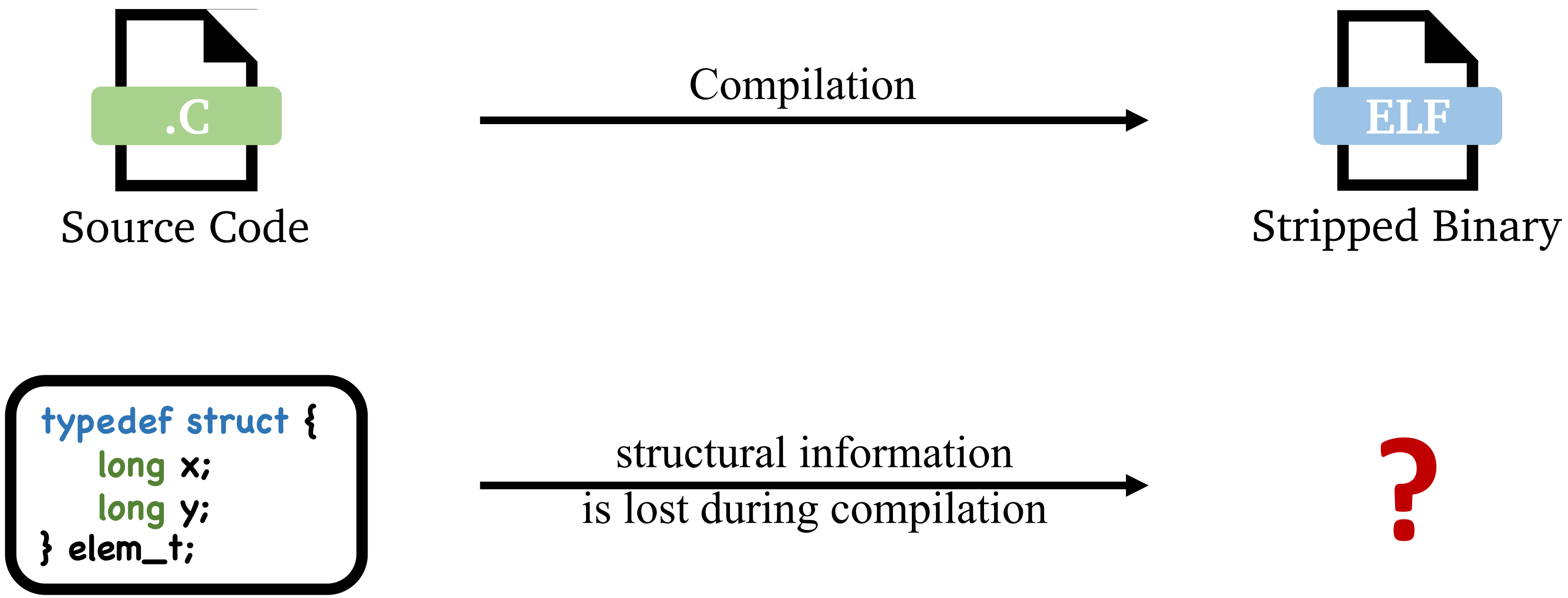

.C
Source Code
Compilation
ELF
Stripped Binary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```c
elem_t v;
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xor rax, rax
mov [rbx + 0x8], eax
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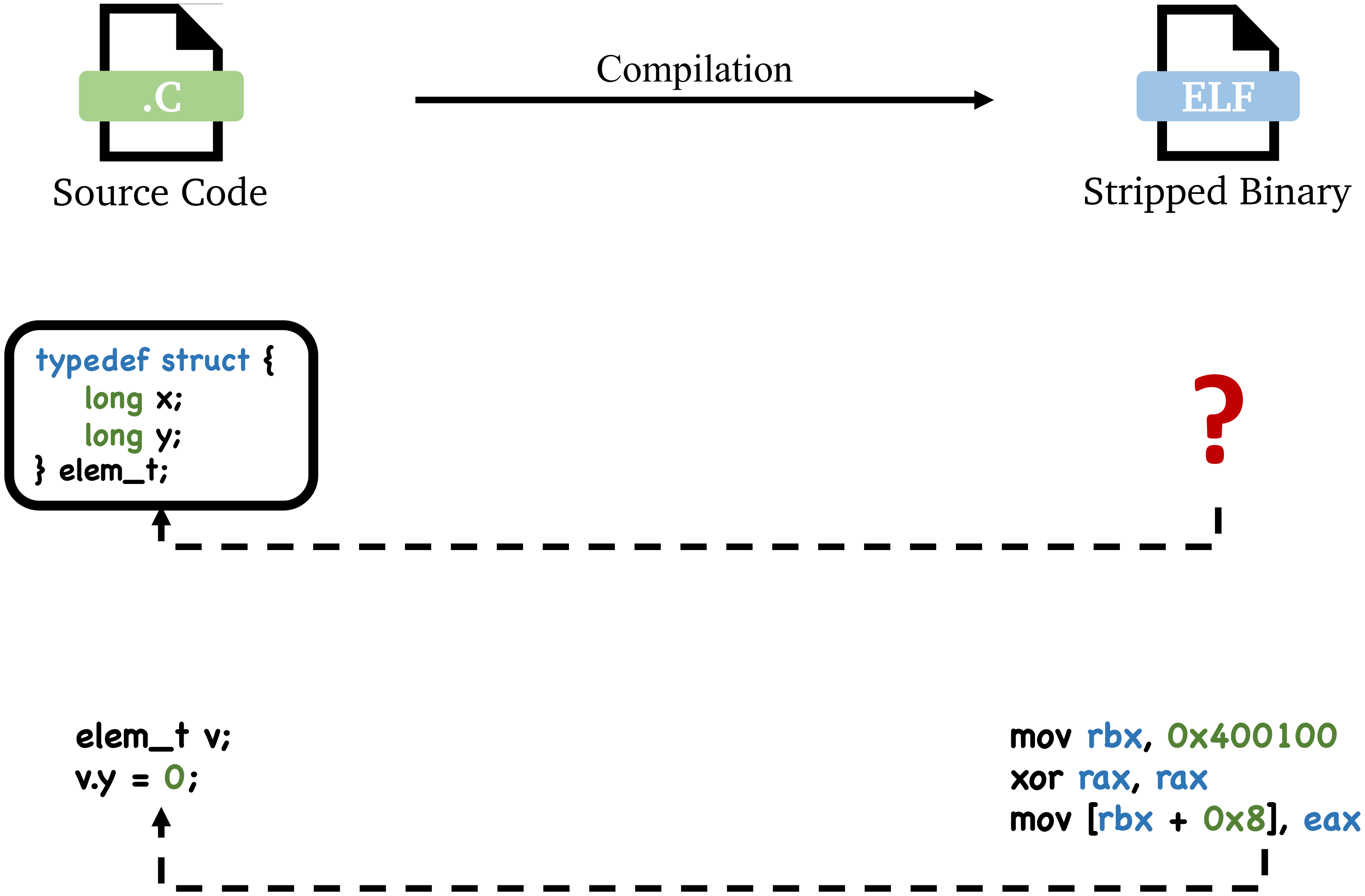
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Variable and data structure recovery is to recover high-level semantic information from the compiled executables.

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- Structure
- Pointer

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call malloc
movdqa xmm0, [rsp + 0x8]
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typedef union {
  int64 u_0[2];
  int128 u_1;
} elem_t;
```

IDA Pro

```
typedef struct {
  int32 s_0[4];
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```

Ghidra

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- Use dynamic analysis to collect program behaviors
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However,

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mov [rsp + 0x8], 0x0
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    *p = v;
  }

  output(p->x, p->y);
}
```

***p** is likely to be structure.

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p->x = v.x;
p->y = v.y;
```

***p** and **v** may be of the same data structure.

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p may point to both stack inlined variable **v** and heap-allocated variable **malloc(...)**, suggesting they may be of the same structure.

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both the heap structure **`malloc(...)`**, and the stack structure **`v`** are accessed by the same instruction.

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How to collect hints?

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- BDA is a path sampling driven per-path abstract interpretation technique.
  - For a given sampled path, BDA **ignores the path feasibility** and abstract interprets the program following the given path. <u>Hints can be collected during abstract interpretation</u>.
  - BDA uses **precise symbolic values** as it interprets individual paths separately, which makes it different from other abstract interpretation techniques like VSA that merges values across paths.

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  - Simply tossing a fair coin at each predicate leads to a distribution that is substantially biased towards short paths.
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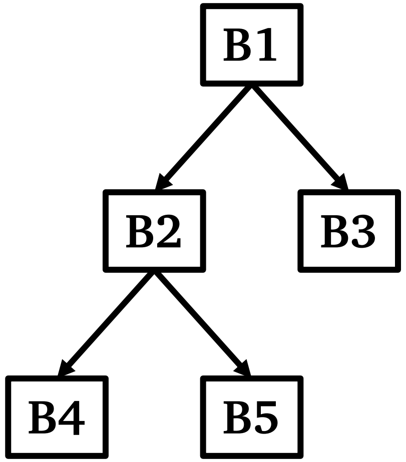

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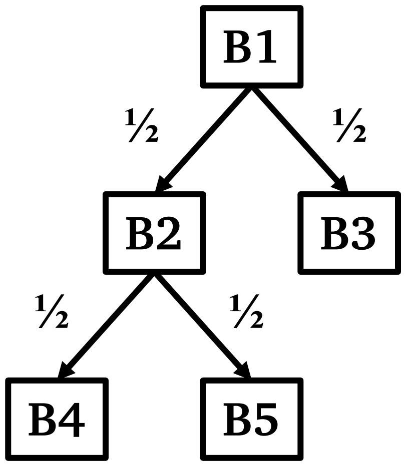

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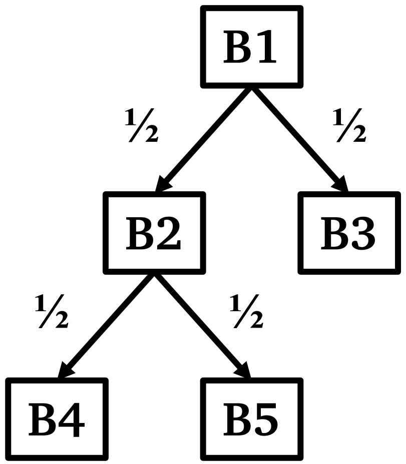

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B1 – B3: ½

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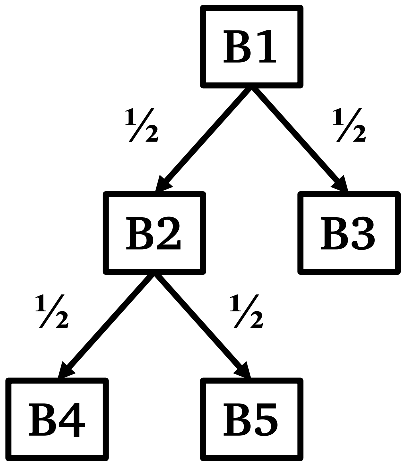

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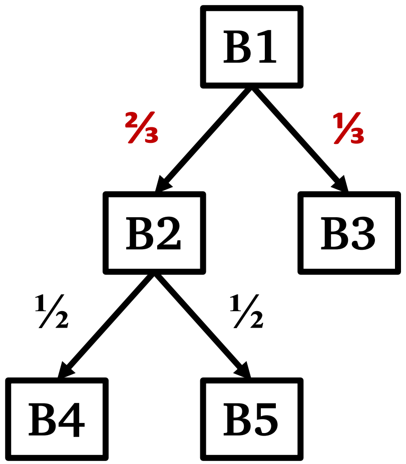

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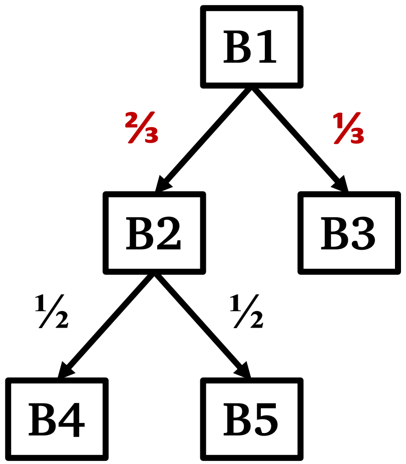

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BDA Sampling:

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→ ***Uncertainty***

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AllocationHint	0.9
PointToHint	0.7
DataFlowHint	0.6
UnifiedAccessHint	0.6

Probabilistic Inference

```
typedef struct {
  int64 x;
  int64 y;
} elem_t;

typedef union {
  elem_t e;
  int128 i;
} union_t;
```

```
elem_t *p_1;    0.9
union_t *p_2;   0.1
```

```
elem_t v;       0.7
int64 v_x;  ┐
int64 v_y;  ┘   0.3
```

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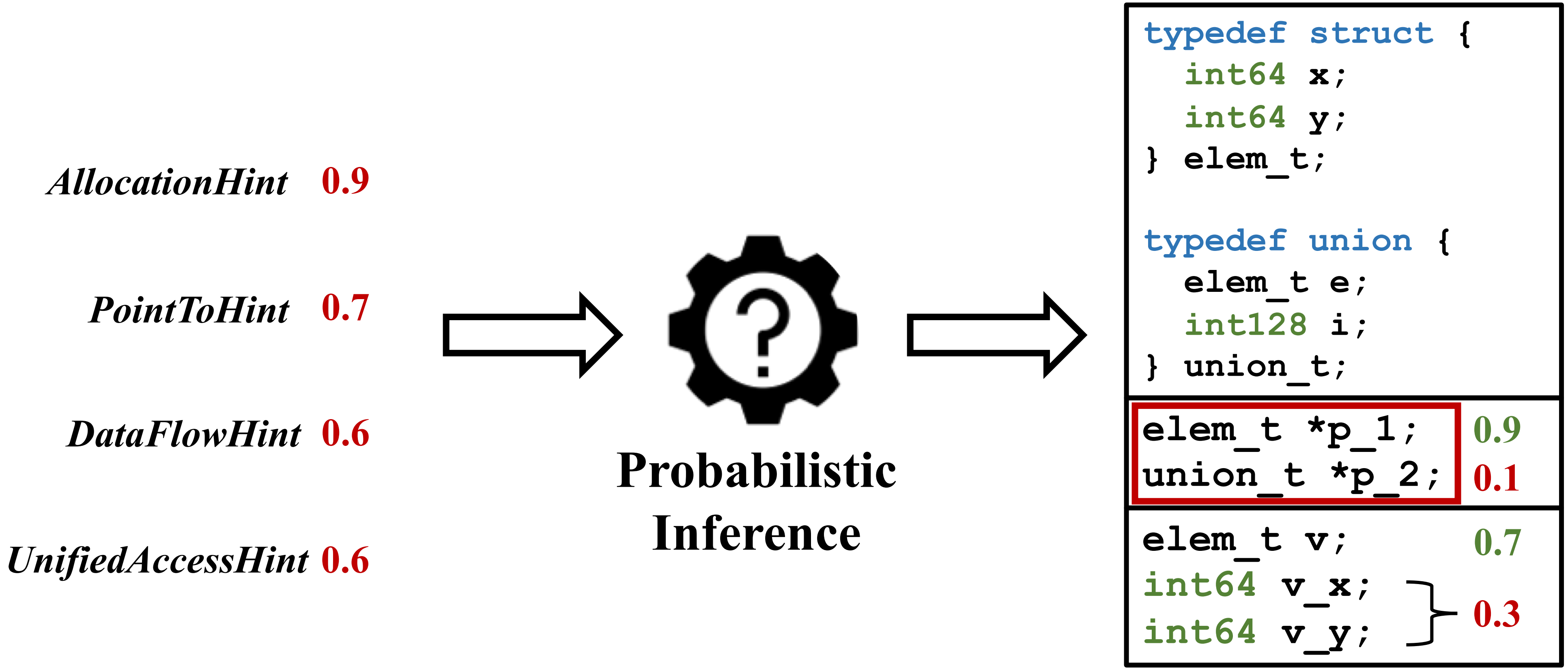

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FieldOf(**`a1`**, **`s`**, **`a2`**): a memory region at address **`a1`** with size **`s`** is a field of a structure at address **`a2`**.

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HomoRegion(`a1`, `a2`, `s`): the memory regions starting at address `a1` and `a2` (with size `s`) have homogeneous structures.

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Probabilistic Constraints: Probabilistic constraints essentially denote probability functions over the random variables involved.

- Correlate these random variables
- Calculate the posterior marginal probabilities for random variables
- The inference denoted by a constraint is probabilistic

Our Techniques

Observation 2: the various kinds of hints in variable/structure recovery can be integrated in a more sophisticated manner using probabilistic inference.

Random Variables: Random variables are introduced to describe variable properties, type properties, and structural properties.

PrimitiveVar(`a`, `s`) ***FieldOf***(`a1`, `s`, `a2`) ***HomoRegion***(`a1`, `a2`, `s`)

Probabilistic Constraints: Probabilistic constraints essentially denote probability functions over the random variables involved.

- Correlate these random variables
- Calculate the posterior marginal probabilities for random variables
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$$\textbf{\textit{DataFlowHint}}(\texttt{a1}, \texttt{a2}, \texttt{s}) \xrightarrow{\textbf{\textit{0.6}}} \textbf{\textit{HomoRegion}}(\texttt{a1}, \texttt{a2}, \texttt{s})$$

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- Correlate these random variables
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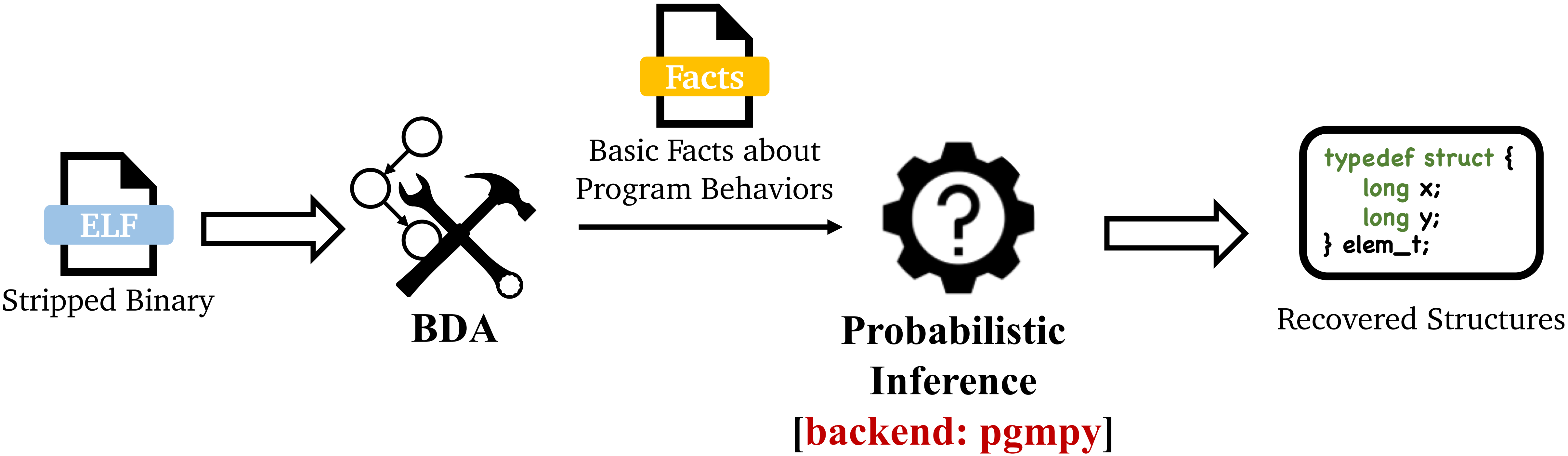
$$\textit{DataFlowHint}(\texttt{a1}, \texttt{a2}, \texttt{s}) \xrightarrow{0.6} \textit{HomoRegion}(\texttt{a1}, \texttt{a2}, \texttt{s})$$

$$\textit{FieldOf}(\texttt{a1}, \texttt{s}, \texttt{a2}) \wedge \textit{HomoRegion}(\texttt{a2}, \texttt{a3}, \texttt{\_}) \xrightarrow{0.9} \textit{FieldOf}(\texttt{a3+(a1-a2)}, \texttt{s}, \texttt{a3})$$

Osprey

Osprey 🦅


Facts
Basic Facts about Program Behaviors
ELF
Stripped Binary
BDA
Probabilistic Inference
[backend: pgmpy]
typedef struct {
long x;
long y;
} elem_t;
Recovered Structures

Evaluation

Evaluation

Benchmark:

- CoreUtils (O0 and O3)
- Benchmark used by Howard Project (O0 and O3)

Ground Truth:

- debugging information

Evaluation

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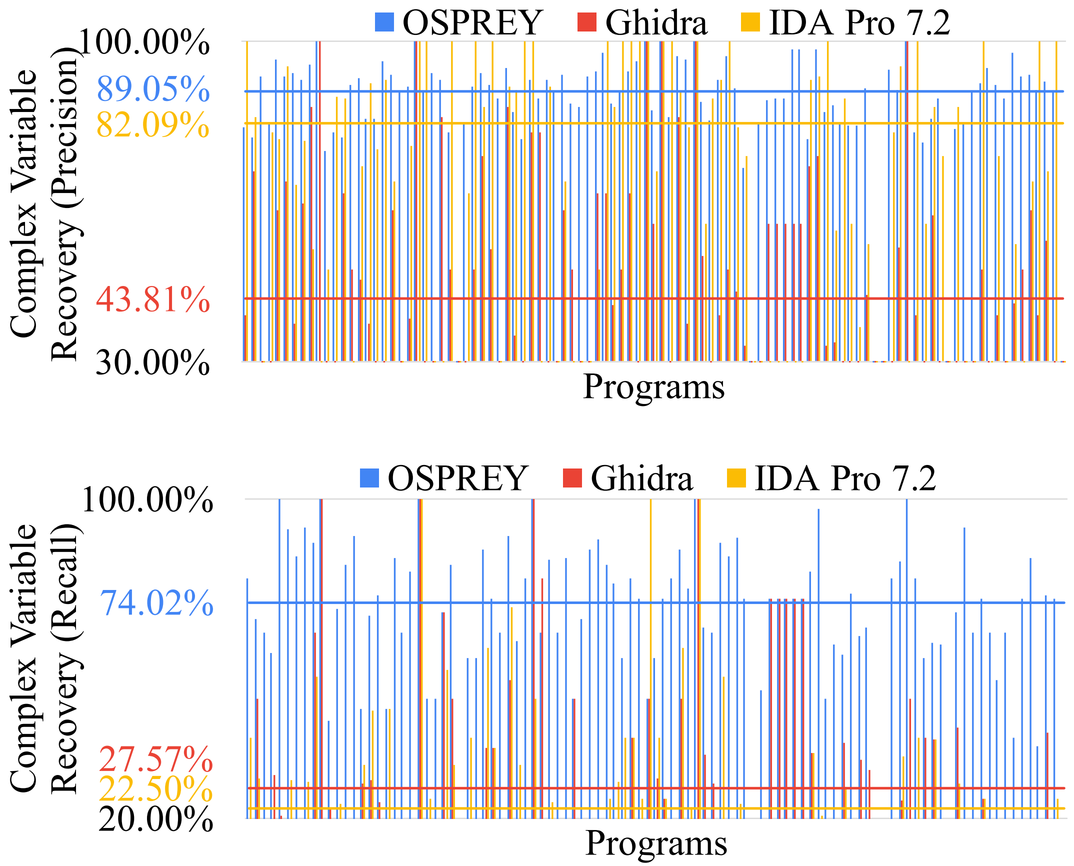
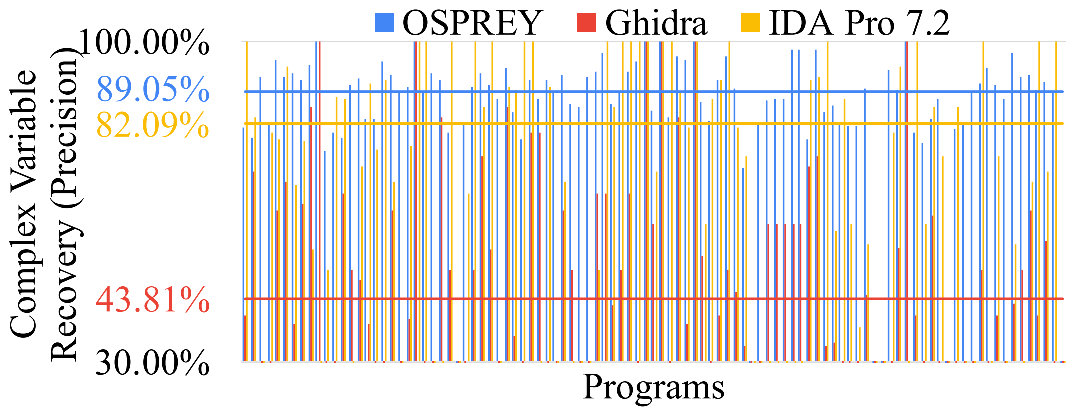
Evaluation: Complex Variable Recovery on CoreUtils

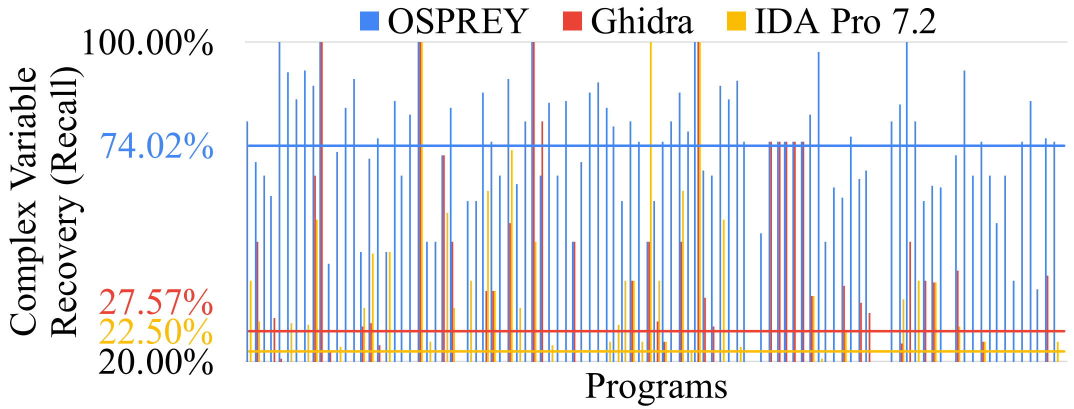


Evaluation: Complex Variable Recovery on CoreUtils

Similar to the standard in the literature, we inspect individual variables.

- Specially, if it is a pointer type, we inspect the structure that is being pointed to.
- Complex variables include structures, unions, arrays and pointers to structures and unions.





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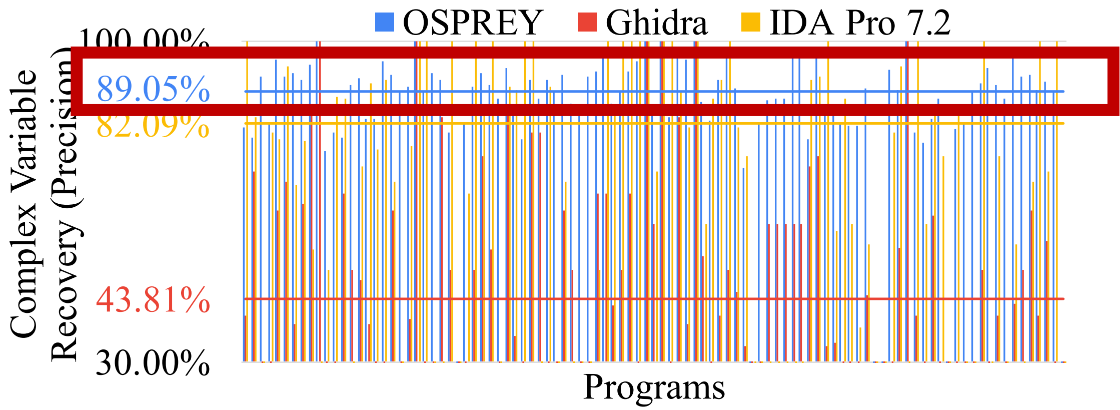

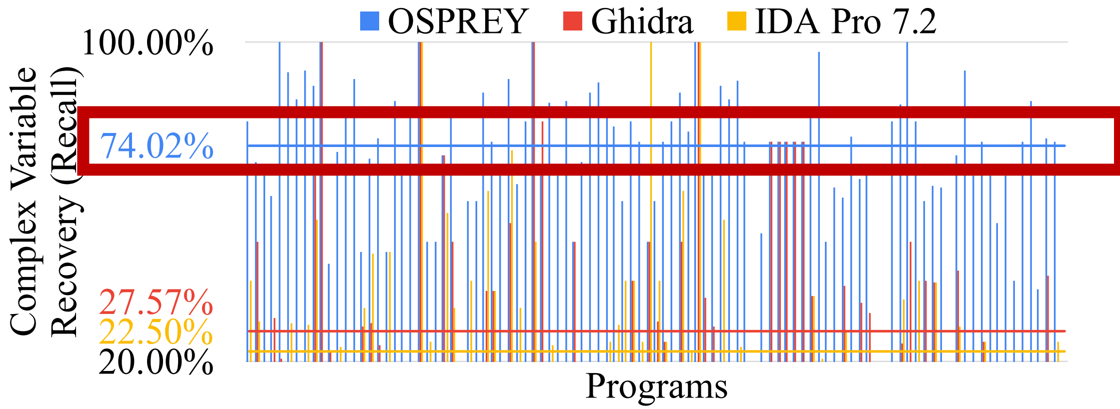

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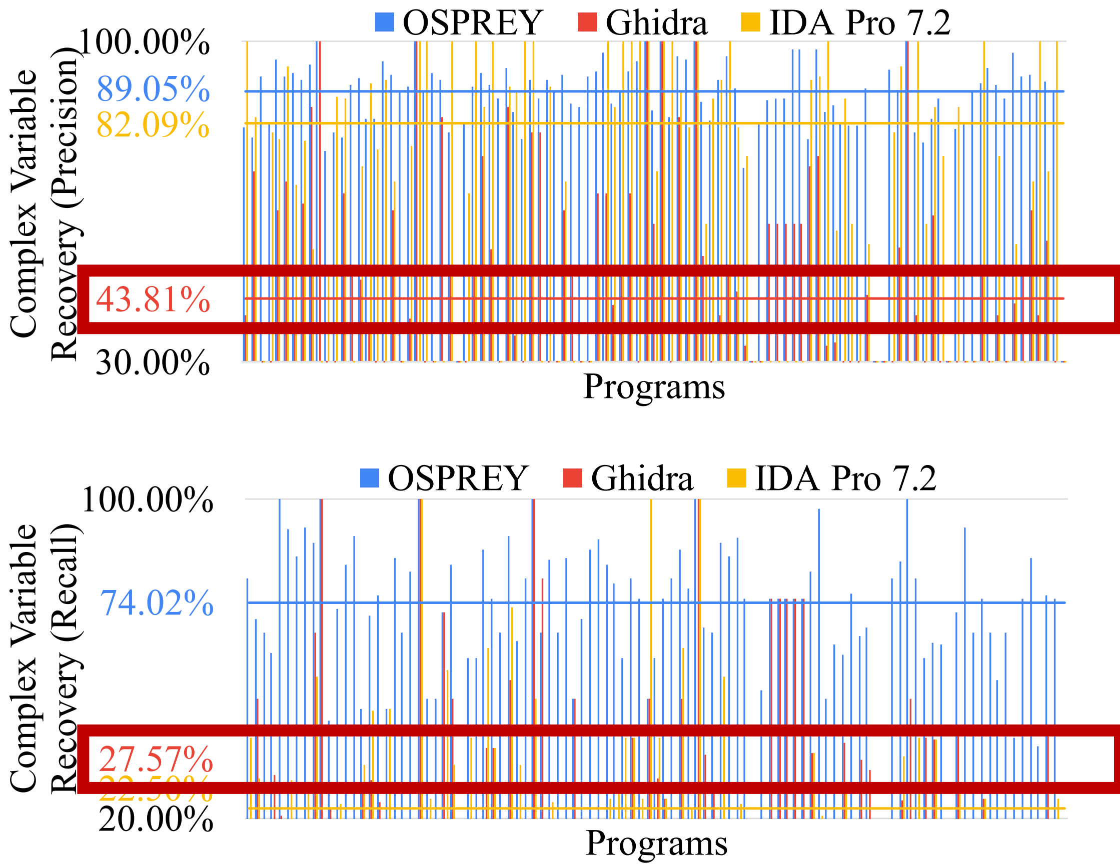

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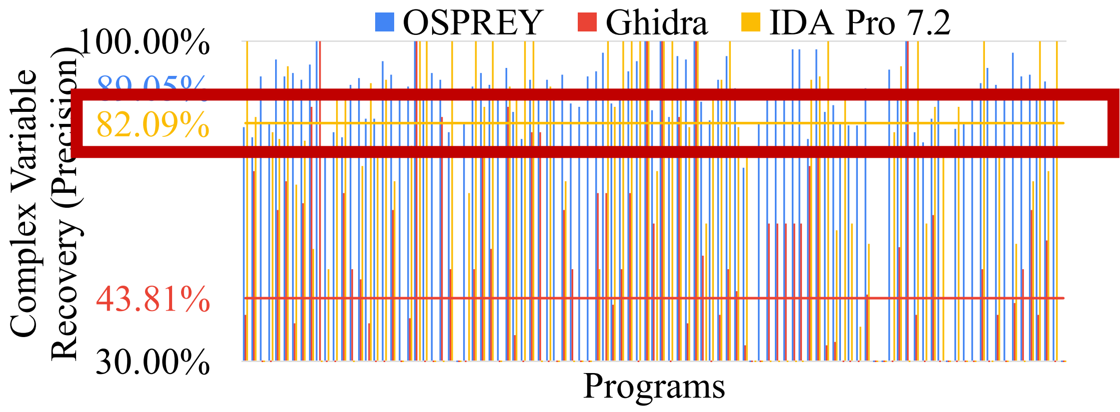

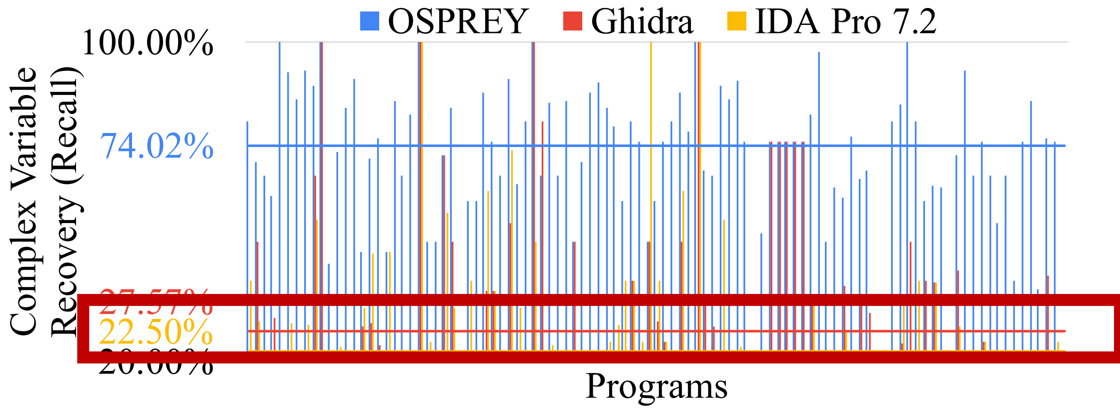

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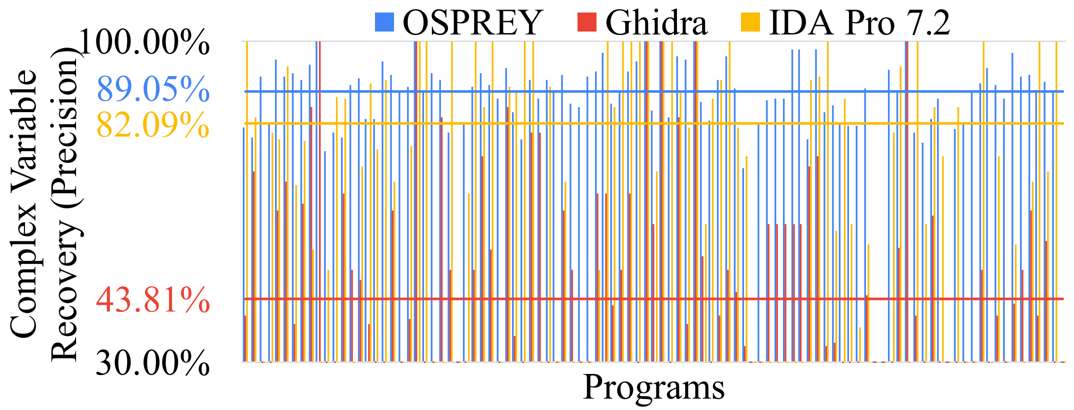

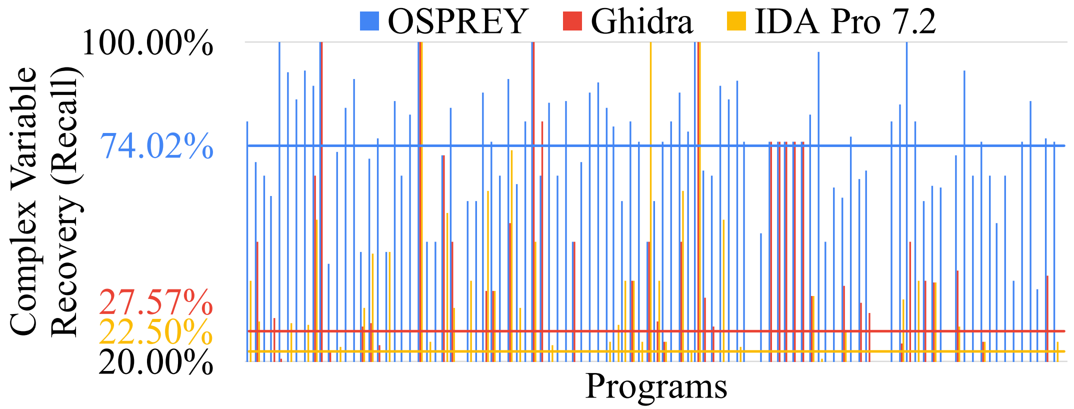

Evaluation: Complex Variable Recovery on CoreUtils

Similar to the standard in the literature, we inspect individual variables.

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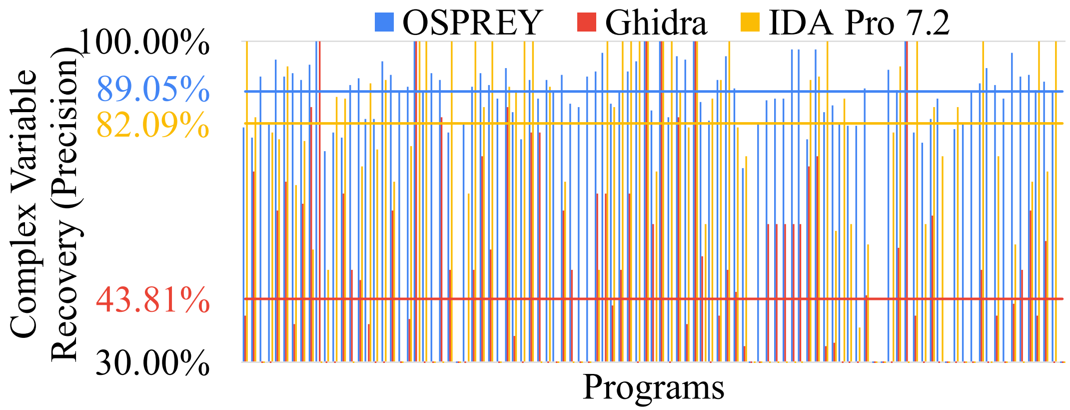
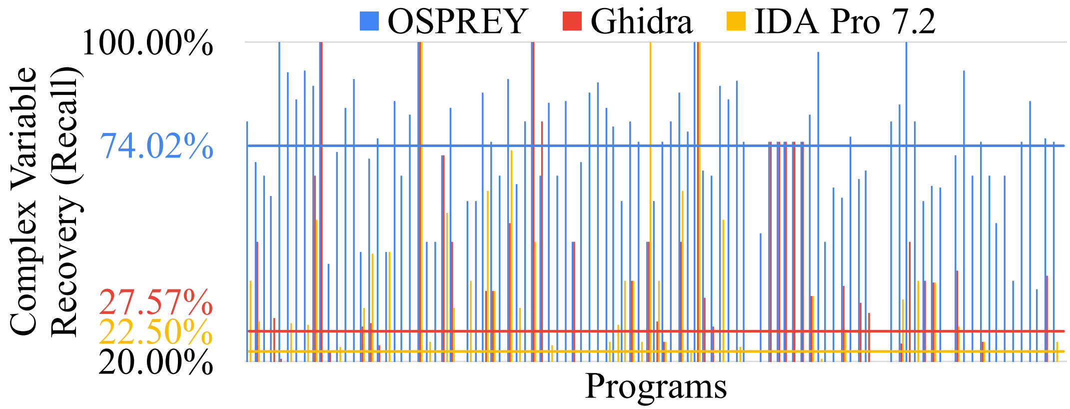
- The recall of OSPREY is around **74%**, more than **2** times higher than Ghidra and IDA Pro.
- The precision of OSPREY also outperforms Ghidra and IDA Pro.
    - We inspect why such improvement, and the main reason is that IDA and Ghidra do not perform complex analysis on recover structure while most complex variables are structure and pointers to structures.





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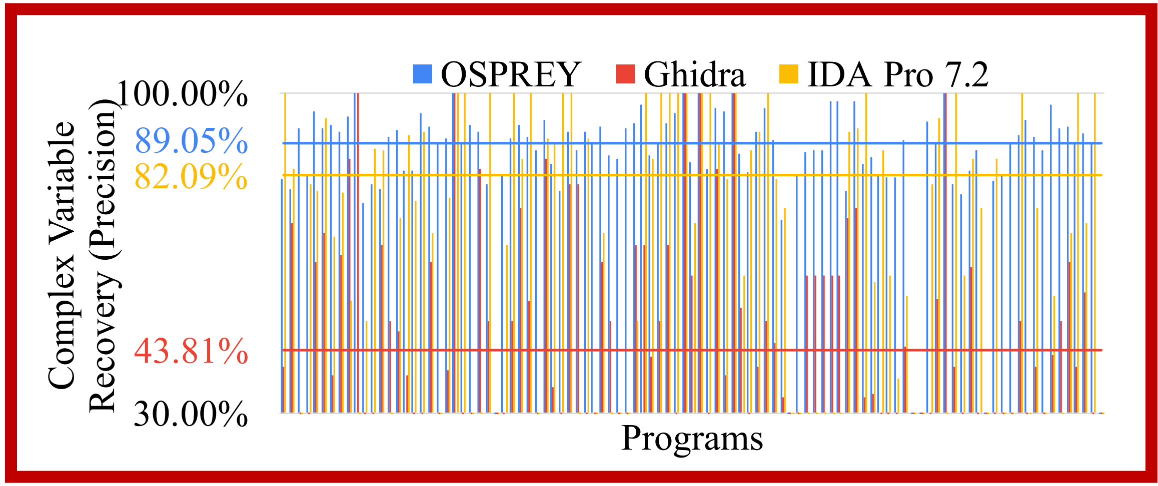

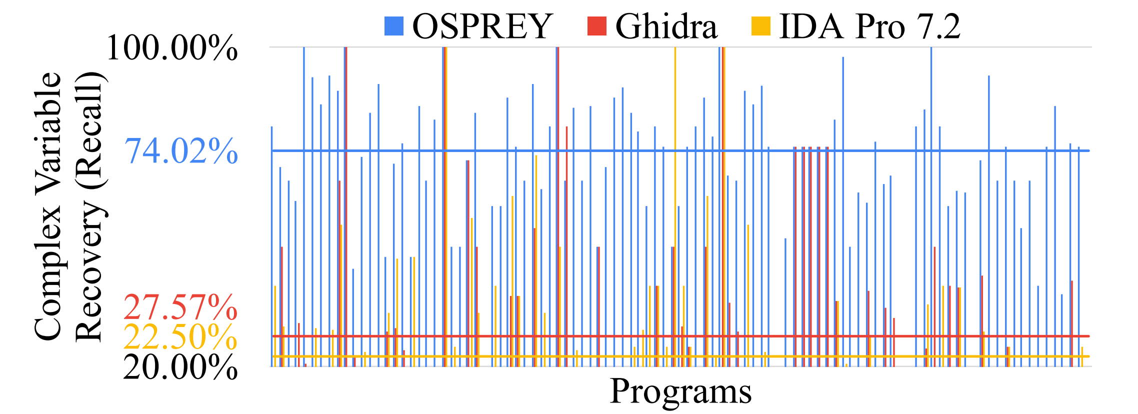

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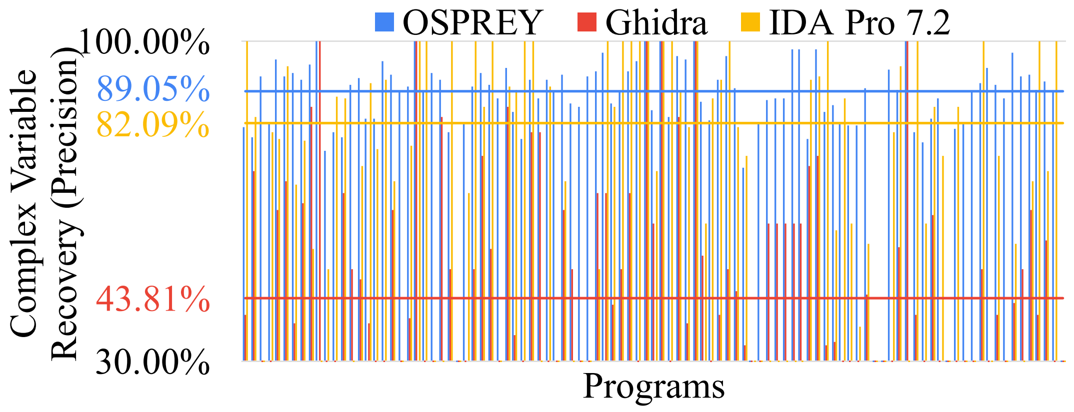

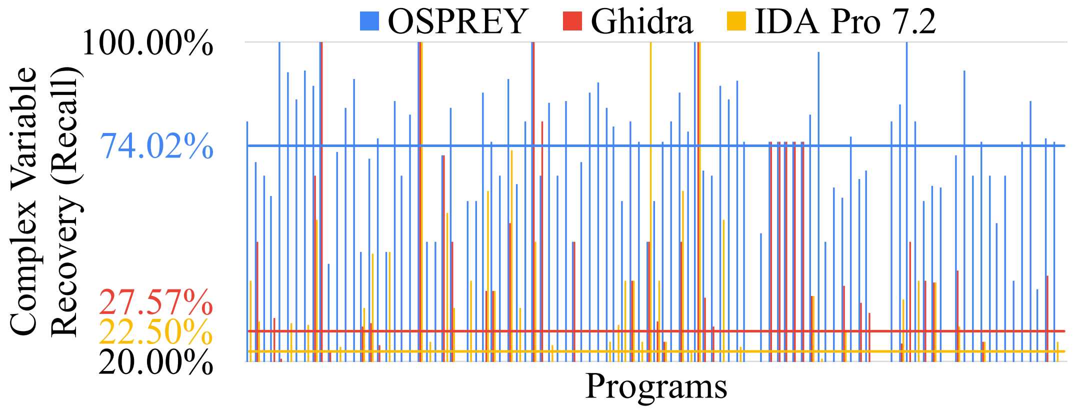

Evaluation: Argument Decompilation Results

```c
int network_rxxx(server *srv)
{
  server *v1; // rbx
  int result; // rax
  size_t v3; // rbp
  server_socket *v4; // r12
  fdnode *v5; // rax
  fdevents *v6; // rdi

  v1 = srv;
  result = fdevent_sxxx(srv->ev);
  if ( result != -1 )
  {
    v3 = 0LL;
    if ( !srv->sockets_disabled )
    {
      while ( v1->srv_sockets.
                    used > v3 )
      {
        v4 = v1->srv_sockets.
                 ptr[v3++];
        v5 = fdevent_gxxx(
                 v1->ev,
                 v4->fd,
                 network_sxxx, v4
        );
        v6 = v1->ev;
        v4->fdn = v5;
        fdevent_fxxx(v6, v5, 1);
      }
    }
    result = 0LL;
  }
  return result;
}
```

IDA Pro w/ debug information

```c
__int32 __fastcall sub_D840(__int64 a1)
{
  _QWORD *v1; // rbx
  __int32 result; // rax
  unsigned __int64 v3; // rbp
  __int64 v4; // r12
  __int64 v5; // rax
  __int64 v6; // rdi

  v1 = (_QWORD *)a1;
  result = sub_12B7A(*(_QWORD *)(a1 + 24));
  if ( (_DWORD)result != -1 )
  {
    v3 = 0LL;
    if ( !*(_DWORD *)(a1 + 100) )
    {
      while ( v1[2] > v3 )

      {
        v4 = *(_QWORD *)(*v1 + 8 * v3++);

        v5 = sub_21860(
               v1[3],
               *(unsigned int *)(v4 + 112),
               sub_18F30, v4
        );
        v6 = v1[3];
        *(_QWORD *)(v4 + 120) = v5;
        sub_219C0(v6, v5, 1);
      }
    }
    result = 0;
  }
  return result;
}
```

Vanilla IDA Pro

```c
__int32 __fastcall sub_D840(struct_C264 *a1)
{
  struct_C264 *v1; // rbx
  __int32 result; // rax
  unsigned __int64 v3; // rbp
  struct_CF4A *v4; // r12
  struct_12A42 *v5; // rax
  struct_12A0E *v6; // rdi

  v1 = a1;
  result = sub_12B7A(a1->ptr_field_28);
  if ( result != -1 )
  {
    v3 = 0LL;
    if ( !a1->dat_field_74 )
    {
      while ( v1->dat_field_10 > v3 )

      {
        v4 = v1->ptr_ptr_field_0[v3++];

        v5 = sub_21860(
                 v1->ptr_field_28,
                 v4->dat_field_10,
                 sub_18F30, v4
        );
        v6 = v1->ptr_field_28;
        v4->ptr_field_18 = v5;
        sub_219C0(v6, v5, 1);
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```

IDA Pro w/ our tool

Evaluation: Argument Decompilation Results

```
int network_rxxx(server *srv)
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  server *v1; // rbx
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  v1 = srv;
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    if ( !srv->sockets_disabled )
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      while ( v1->srv_sockets.
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      {
        v4 = v1->srv_sockets.
                  ptr[v3++];
        v5 = fdevent_gxxx(
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                  v4->fd,
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        v6 = v1->ev;
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IDA Pro w/ debug information

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    if ( !*(_DWORD *)(a1 + 100) )
    {
      while ( v1[2] > v3 )
      {
        v4 = *(_QWORD *)(*v1 + 8 * v3++);

        v5 = sub_21860(
               v1[3],
               *(unsigned int *)(v4 + 112),
               sub_18F30, v4
        );
        v6 = v1[3];
        *(_QWORD *)(v4 + 120) = v5;
        sub_219C0(v6, v5, 1);
      }
    }
    result = 0;
  }
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}
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Vanilla IDA Pro

```
__int32 __fastcall sub_D840(struct_C264 *a1)
{
  struct_C264 *v1; // rbx
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  struct_12A42 *v5; // rax
  struct_12A0E *v6; // rdi

  v1 = a1;
  result = sub_12B7A(a1->ptr_field_28);
  if ( result != -1 )
  {
    v3 = 0LL;
    if ( !a1->dat_field_74 )
    {
      while ( v1->dat_field_10 > v3 )

      {
        v4 = v1->ptr_ptr_field_0[v3++];

        v5 = sub_21860(
                 v1->ptr_field_28,
                 v4->dat_field_10,
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        v6 = v1->ptr_field_28;
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IDA Pro w/ our tool

Evaluation: Argument Decompilation Results

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IDA Pro w/ debug information

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  if ( (_DWORD)result != -1 )
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    v3 = 0LL;
    if ( !*(_DWORD *)(a1 + 100) )
    {
      while ( v1[2] > v3 )

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        );
        v6 = v1[3];
        *(_QWORD *)(v4 + 120) = v5;
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    result = 0;
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```

Vanilla IDA Pro

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      while ( v1->dat_field_10 > v3 )

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  }
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IDA Pro w/ our tool

Evaluation: Argument Decompilation Results

```c
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  v1 = srv;
  result = fdevent_sxxx(srv->ev);
  if ( result != -1 )
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    v3 = 0LL;
    if ( !srv->sockets_disabled )
    {
      while ( v1->srv_sockets.
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IDA Pro w/ our tool

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  fdevents *v6; // rdi

  v1 = srv;
  result = fdevent_sxxx(srv->ev);
  if ( result != -1 )
  {
    v3 = 0LL;
    if ( !srv->sockets_disabled )
    {
      while ( v1->srv_sockets.
                    used > v3 )
      {
        v4 = v1->srv_sockets.
                 ptr[v3++];
        v5 = fdevent_gxxx(
                 v1->ev,
                 v4->fd,
                 network_sxxx, v4
        );
        v6 = v1->ev;
        v4->fdn = v5;
        fdevent_fxxx(v6, v5, 1);
      }
    }
    result = 0LL;
  }
  return result;
}
```

IDA Pro w/ debug information

```
__int32 __fastcall sub_D840(__int64 a1)
{
  _QWORD *v1; // rbx
  __int32 result; // rax
  unsigned __int64 v3; // rbp
  __int64 v4; // r12
  __int64 v5; // rax
  __int64 v6; // rdi

  v1 = (_QWORD *)a1;
  result = sub_12B7A(*(_QWORD *)(a1 + 24));
  if ( (_DWORD)result != -1 )
  {
    v3 = 0LL;
    if ( !*(_DWORD *)(a1 + 100) )
    {
      while ( v1[2] > v3 )
      {
        v4 = *(_QWORD *)(*v1 + 8 * v3++);
        v5 = sub_21860(
               v1[3],
               *(unsigned int *)(v4 + 112),
               sub_18F30, v4
        );
        v6 = v1[3];
        *(_QWORD *)(v4 + 120) = v5;
        sub_219C0(v6, v5, 1);
      }
    }
    result = 0;
  }
  return result;
}
```

Vanilla IDA Pro

```
__int32 __fastcall sub_D840(struct_C264 *a1)
{
  struct_C264 *v1; // rbx
  __int32 result; // rax
  unsigned __int64 v3; // rbp
  struct_CF4A *v4; // r12
  struct_12A42 *v5; // rax
  struct_12A0E *v6; // rdi

  v1 = a1;
  result = sub_12B7A(a1->ptr_field_28);
  if ( result != -1 )
  {
    v3 = 0LL;
    if ( !a1->dat_field_74 )
    {
      while ( v1->dat_field_10 > v3 )
      {
        v4 = v1->ptr_ptr_field_0[v3++];
        v5 = sub_21860(
                 v1->ptr_field_28,
                 v4->dat_field_10,
                 sub_18F30, v4
        );
        v6 = v1->ptr_field_28;
        v4->ptr_field_18 = v5;
        sub_219C0(v6, v5, 1);
      }
    }
    result = 0;
  }
  return result;
}
```

IDA Pro w/ our tool

Evaluation: Argument Decompilation Results

```
int network_rxxx(server *srv)
{
  server *v1; // rbx
  int result; // rax
  size_t v3; // rbp
  server_socket *v4; // r12
  fdnode *v5; // rax
  fdevents *v6; // rdi

  v1 = srv;
  result = fdevent_sxxx(srv->ev);
  if ( result != -1 )
  {
    v3 = 0LL;
    if ( !srv->sockets_disabled )
    {
      while ( v1->srv_sockets.
              used > v3 )
      {
        v4 = v1->srv_sockets.
             ptr[v3++];
        v5 = fdevent_gxxx(
             v1->ev,
             v4->fd,
             network_sxxx, v4
        );
        v6 = v1->ev;
        v4->fdn = v5;
        fdevent_fxxx(v6, v5, 1);
      }
    }
    result = 0LL;
  }
  return result;
}
```

IDA Pro w/ debug information

```
__int32 __fastcall sub_D840(__int64 a1)
{
  _QWORD *v1; // rbx
  __int32 result; // rax
  unsigned __int64 v3; // rbp
  __int64 v4; // r12
  __int64 v5; // rax
  __int64 v6; // rdi

  v1 = (_QWORD *)a1;
  result = sub_12B7A(*(_QWORD *)(a1 + 24));
  if ( (_DWORD)result != -1 )
  {
    v3 = 0LL;
    if ( !*(_DWORD *)(a1 + 100) )
    {
      while ( v1[2] > v3 )
      {
        v4 = *(_QWORD *)(*v1 + 8 * v3++);
        v5 = sub_21860(
               v1[3],
               *(unsigned int *)(v4 + 112),
               sub_18F30, v4
        );
        v6 = v1[3];
        *(_QWORD *)(v4 + 120) = v5;
        sub_219C0(v6, v5, 1);
      }
    }
    result = 0;
  }
  return result;
}
```

Vanilla IDA Pro

```
__int32 __fastcall sub_D840(struct_C264 *a1)
{
  struct_C264 *v1; // rbx
  __int32 result; // rax
  unsigned __int64 v3; // rbp
  struct_CF4A *v4; // r12
  struct_12A42 *v5; // rax
  struct_12A0E *v6; // rdi

  v1 = a1;
  result = sub_12B7A(a1->ptr_field_28);
  if ( result != -1 )
  {
    v3 = 0LL;
    if ( !a1->dat_field_74 )
    {
      while ( v1->dat_field_10 > v3 )
      {
        v4 = v1->ptr_ptr_field_0[v3++];
        v5 = sub_21860(
               v1->ptr_field_28,
               v4->dat_field_10,
               sub_18F30, v4
        );
        v6 = v1->ptr_field_28;
        v4->ptr_field_18 = v5;
        sub_219C0(v6, v5, 1);
      }
    }
    result = 0;
  }
  return result;
}
```

IDA Pro w/ our tool

Evaluation: Argument Decompilation Results

```c
int network_rxxx(server *srv)
{
  server *v1; // rbx
  int result; // rax
  size_t v3; // rbp
  server_socket *v4; // r12
  fdnode *v5; // rax
  fdevents *v6; // rdi

  v1 = srv;
  result = fdevent_sxxx(srv->ev);
  if ( result != -1 )
  {
    v3 = 0LL;
    if ( !srv->sockets_disabled )
    {
      while ( v1->srv_sockets.
                    used > v3 )
      {
        v4 = v1->srv_sockets.
                 ptr[v3++];
        v5 = fdevent_gxxx(
                 v1->ev,
                 v4->fd,
                 network_sxxx, v4
        );
        v6 = v1->ev;
        v4->fdn = v5;
        fdevent_fxxx(v6, v5, 1);
      }
    }
    result = 0LL;
  }
  return result;
}
```

IDA Pro w/ debug information

```c
__int32 __fastcall sub_D840(__int64 a1)
{
  _QWORD *v1; // rbx
  __int32 result; // rax
  unsigned __int64 v3; // rbp
  __int64 v4; // r12
  __int64 v5; // rax
  __int64 v6; // rdi

  v1 = (_QWORD *)a1;
  result = sub_12B7A(*(_QWORD *)(a1 + 24));
  if ( (_DWORD)result != -1 )
  {
    v3 = 0LL;
    if ( !*(_DWORD *)(a1 + 100) )
    {
      while ( v1[2] > v3 )
      {
        v4 = *(_QWORD *)(*v1 + 8 * v3++);
        v5 = sub_21860(
               v1[3],
               *(unsigned int *)(v4 + 112),
               sub_18F30, v4
        );
        v6 = v1[3];
        *(_QWORD *)(v4 + 120) = v5;
        sub_219C0(v6, v5, 1);
      }
    }
    result = 0;
  }
  return result;
}
```

Vanilla IDA Pro

```c
__int32 __fastcall sub_D840(struct_C264 *a1)
{
  struct_C264 *v1; // rbx
  __int32 result; // rax
  unsigned __int64 v3; // rbp
  struct_CF4A *v4; // r12
  struct_12A42 *v5; // rax
  struct_12A0E *v6; // rdi

  v1 = a1;
  result = sub_12B7A(a1->ptr_field_28);
  if ( result != -1 )
  {
    v3 = 0LL;
    if ( !a1->dat_field_74 )
    {
      while ( v1->dat_field_10 > v3 )
      {
        v4 = v1->ptr_ptr_field_0[v3++];
        v5 = sub_21860(
               v1->ptr_field_28,
               v4->dat_field_10,
               sub_18F30, v4
        );
        v6 = v1->ptr_field_28;
        v4->ptr_field_18 = v5;
        sub_219C0(v6, v5, 1);
      }
    }
    result = 0;
  }
  return result;
}
```

IDA Pro w/ our tool

Related Works

Variable recovery and type inference for stripped binary:

- Slowinska, Asia, Traian Stancescu, and Herbert Bos. "Howard: A Dynamic Excavator for Reverse Engineering Data Structures." *NDSS*. 2011.
- Shoshitaishvili, Yan, et al. "Sok:(state of) the art of war: Offensive techniques in binary analysis." *2016 IEEE Symposium on Security and Privacy (SP)*. IEEE, 2016.
- Lee, JongHyup, Thanassis Avgerinos, and David Brumley. "TIE: Principled reverse engineering of types in binary programs." (2011).
- Lin, Zhiqiang, Xiangyu Zhang, and Dongyan Xu. "Automatic reverse engineering of data structures from binary execution." *Proceedings of the 11th Annual Information Security Symposium*. 2010.

Probabilistic Program Analysis:

- Geldenhuys, Jaco, Matthew B. Dwyer, and Willem Visser. "Probabilistic symbolic execution." *Proceedings of the 2012 International Symposium on Software Testing and Analysis*. 2012.
- Borges, Mateus, et al. "Iterative distribution-aware sampling for probabilistic symbolic execution." *Proceedings of the 2015 10th Joint Meeting on Foundations of Software Engineering*. 2015.
- Kwiatkowska, Marta, Gethin Norman, and David Parker. "PRISM 4.0: Verification of probabilistic real-time systems." *International conference on computer aided verification*. Springer, Berlin, Heidelberg, 2011.
- Filieri, Antonio, Carlo Ghezzi, and Giordano Tamburrelli. "Run-time efficient probabilistic model checking." *2011 33rd International Conference on Software Engineering (ICSE)*. IEEE, 2011.

We develop a novel probabilistic variable and data structure recovery technique for stripped binaries.

- It leverages an advanced data-flow technique, BDA, to collect program behaviors.
- It features using random variables to denote the likelihood of recovery results such that a large number of various kinds of hints can be integrated with the inherent uncertainty considered.
- It achieves the state-of-the-art inversing results.

We develop a novel probabilistic variable and data structure recovery technique for stripped binaries.

- It leverages an advanced data-flow technique, BDA, to collect program behaviors.
- It features using random variables to denote the likelihood of recovery results such that a large number of various kinds of hints can be integrated with the inherent uncertainty considered.
- It achieves the state-of-the-art inversing results.

Thanks!