WYSINWYX: What You See Is Not What You eXecute
(Static Analysis of Executables)

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Work done while at UW Madison with J.Lim (UW), T. Reps (UW, GrammaTech), T. Teitelbaum (Cornell, GrammaTech)

The Vision

- A tool for analyzing executables
  - to find security vulnerabilities and bugs
  - to analyze/understand malicious code like viruses/worms
  - to perform code obfuscation and de-obfuscation
  - to perform de-compilation
  - etc.,

- Who cares?
  - CERT, Govt. agencies like NSA, etc
  - Anti-Virus/Anti-Malware companies
  - Even researchers in program analysis/verification should!

Why Executables? (1)

- Source code may not be available
  - Viruses and Worms
  - Commercial-Off-The-Shelf (COTS) components
  - Browser plug-ins
  - Java applets
  - etc.,
- Allows analysis of library code
  - Otherwise, must model library code with stubs
  - In turn, helps analysis of source-code
- The usual suspects . . .

Why Executables? (2)

- Executables can be a better platform for finding security vulnerabilities
  - Many exploits utilize particular quirks of the compiler (e.g., details of memory-layout or register usage)

- Analysis of source code may give incorrect answers!
  - "WYSINWYX": What You See Is Not What You eXecute

- Analysis of source code may be less accurate!
  - Executable reflects actual behaviors that may arise
  - Allows us to take into account platform-specific aspects
    - e.g., order of evaluation of arguments of a function

Example: Minimizing Data Lifetime?

- Windows login process
  - keeps a user's password in the heap
- Should minimize data lifetime by
  - clearing memory after login
  - calling free()
- May not work
  - the compiler might "optimize" away the memory-clearing code ("dead-code" elimination)

```
memset(buffer, '\0', len);
free(buffer);
```

$\Longrightarrow$

```
free(buffer);
```

Puzzle

```
int callee(int a, int b) {
  int local;
  if (local == 5) return 1;
  else return 2;
}

int main() {
  int c = 5;
  int d = 7;

  int v = callee(c,d);
  // What is the value of v here?
  return 0;
}
```

Answer: 1
(for the Microsoft compiler)

Tutorial on x86 (Intel Syntax)

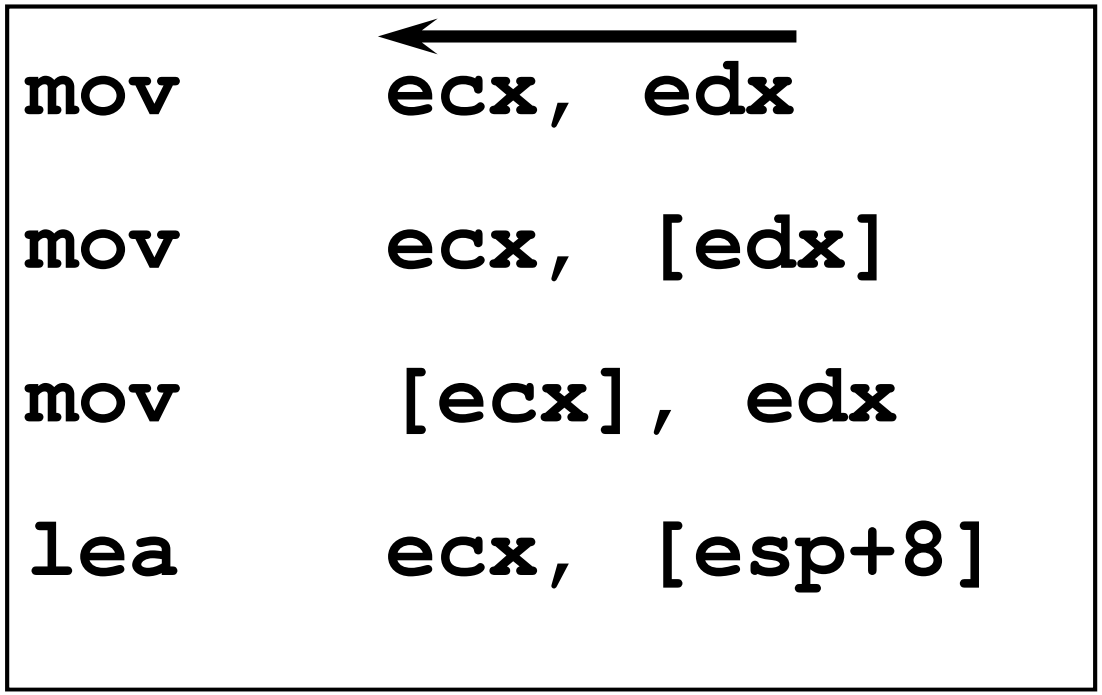
```
 p = q;

 p = *q;

*p = q;

 p = &a[2];
```

Tutorial on x86 (Intel Syntax)



```
mov     ecx, edx
mov     ecx, [edx]
mov     [ecx], edx
lea     ecx, [esp+8]
```

```
ecx = edx;
ecx = *edx;
*ecx = edx;
ecx = &a[2];
```

Standard prolog		Prolog for 1 local	
push	ebp	push	ebp
mov	ebp, esp	mov	ebp, esp
sub	esp, 4	push	ecx

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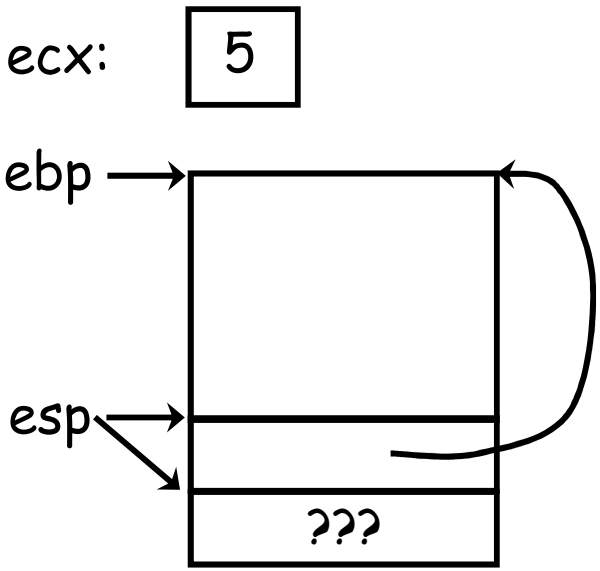

Standard prolog

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Prolog for 1 local

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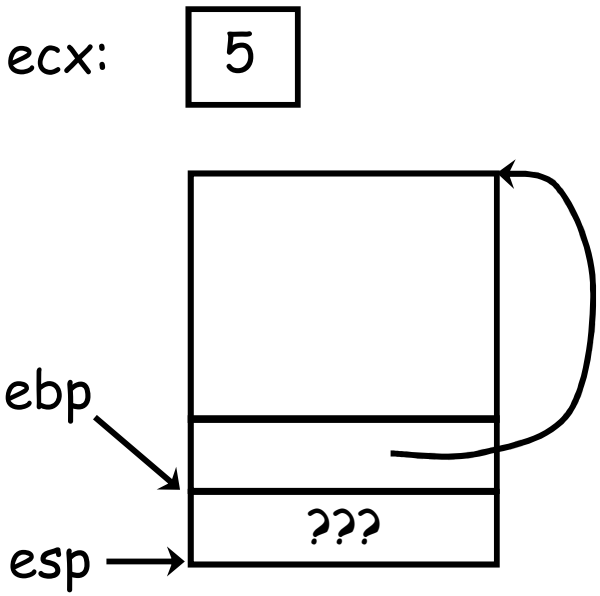

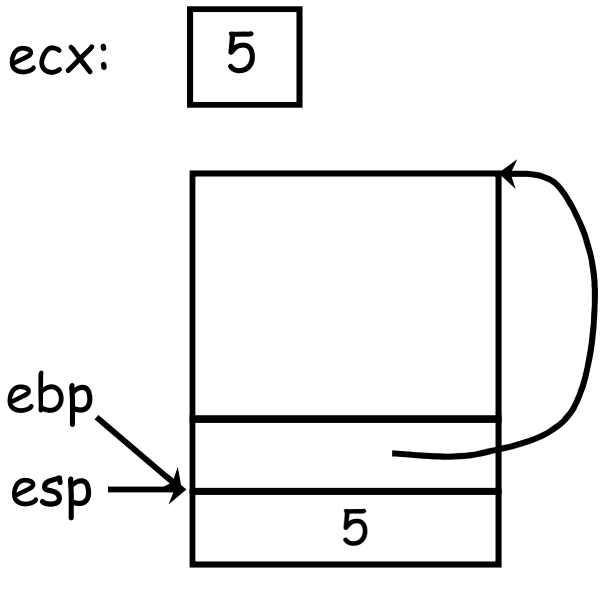

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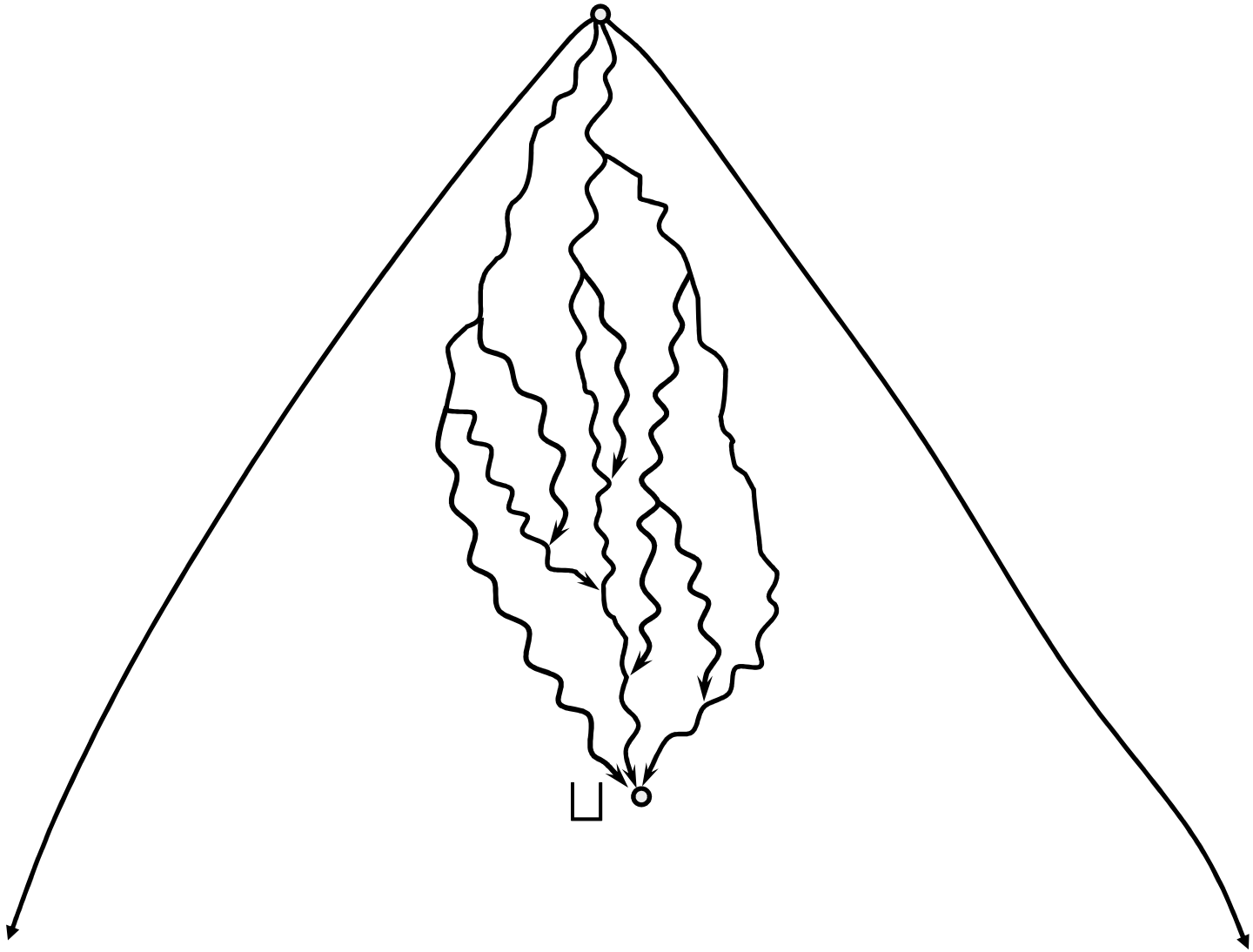
push	ebp	push	ebp
mov	ebp, esp	mov	ebp, esp
sub	esp, 4	push	ecx

Answer: 1
(for the Microsoft compiler)

```
mov   [ebp+var_8], 5
mov   [ebp+var_C], 7
mov   eax, [ebp+var_C]
push  eax
mov   ecx, [ebp+var_8]
push  ecx
call  _callee
...
```

"Platform-Specific" ⇒ Fewer Behaviors



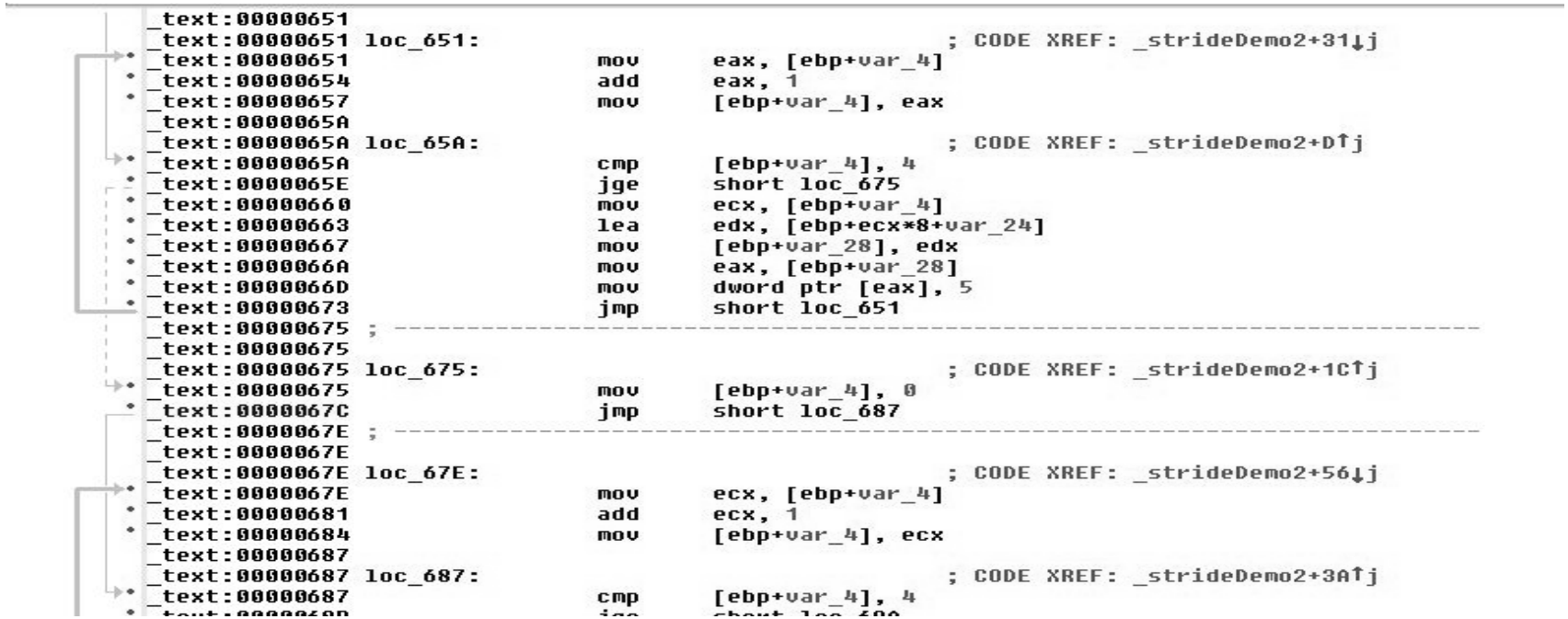
Analyze source code or executable?

An issue for any verification/analysis method

- Theorem Proving
- Model Checking
- Abstract Interpretation

Executable-Analysis Tools

- Disassemblers
  - Distinguish code and data
  - Requires manual effort to understand the program
  - e.g., IDAPro, OllyDbg, etc.



Executable-Analysis Tools

- Tools that perform data-flow analysis
  - e.g., EEL, Tools by Cifuentes, Debbabi, Debray
  - Able to track only data movements via registers
  - Poor treatment of memory operations
    - Overly conservative treatment ⇒ many false positives
    - Non-conservative treatment ⇒ many false negatives
  - Some tools aid in decompilation

```
mov [ebp – 10], 20
. . .
mov eax, [ebp – 10]
mov ebx, [ecx]
```

```
mov eax, [ebp – 10]
mov [ecx], eax
```

```
mov [ecx], [ebp - 10]
```

Executable-Analysis Tools

- Ad-hoc special-purpose analyzers
  - An analyzer to identify indirect calls
  - An analyzer to identify strings
  - An analyzer to check stack height
  - etc.,
- Program analysis frameworks
  - Rely on symbol-table/debugging info
  - e.g., Atom, Vulcan, Phoenix

What is the holy grail?

- General platform for analyzing executables
- Tracks data movement through memory
  - including heap
- Must not rely on debugging information
- Gives information to build further analysis
  - like a compiler front-end plus some more

Outline

- CodeSurfer/x86 architecture
- Challenges
- Core Analysis Algorithms
  - Recovering variable-like entities (a-loc)
  - Value-set Analysis (VSA)
  - Other Algorithms
- Device-Driver Analysis
  - Improved a-loc recovery

- What Next?

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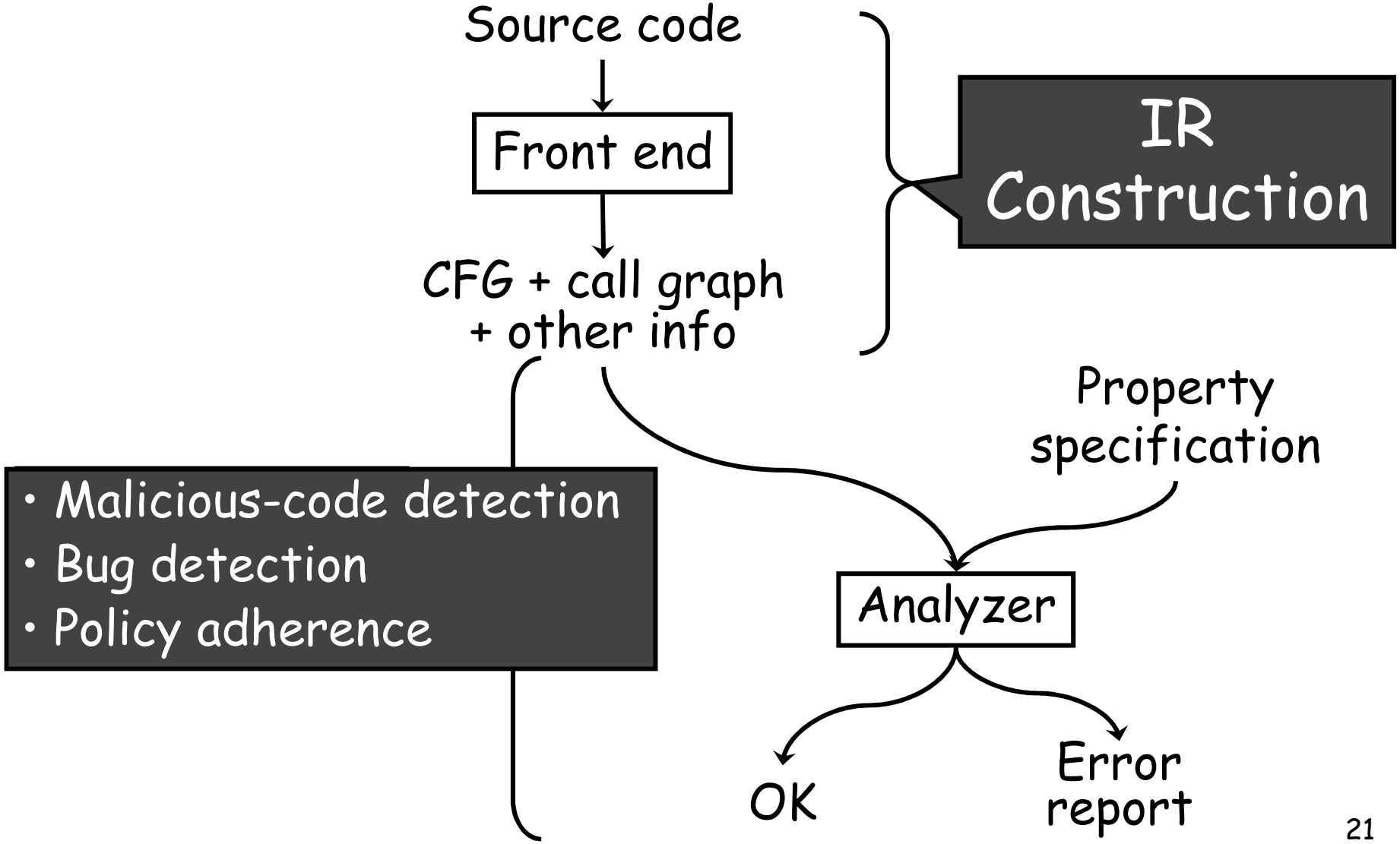
Static Program-Analysis Tools



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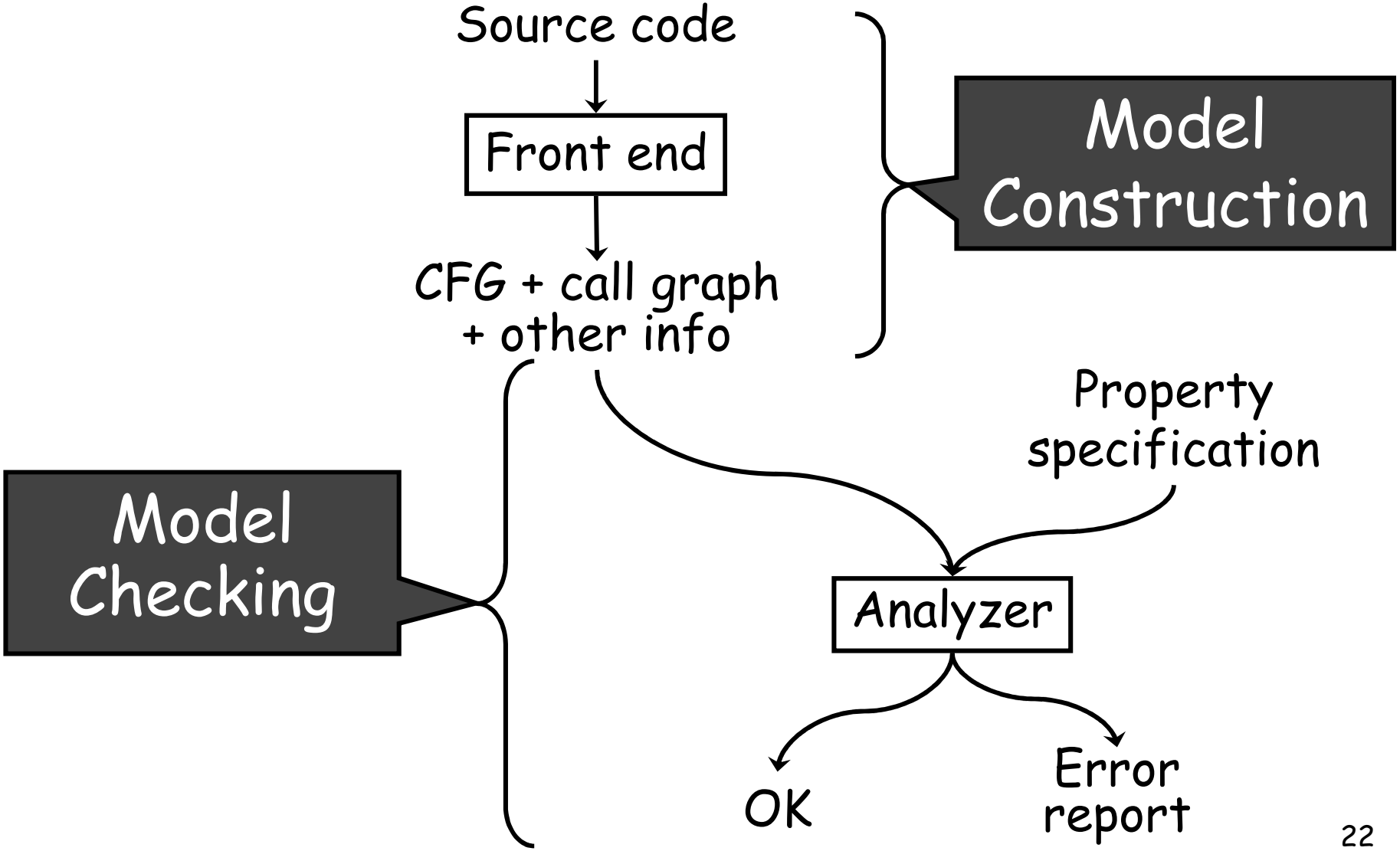

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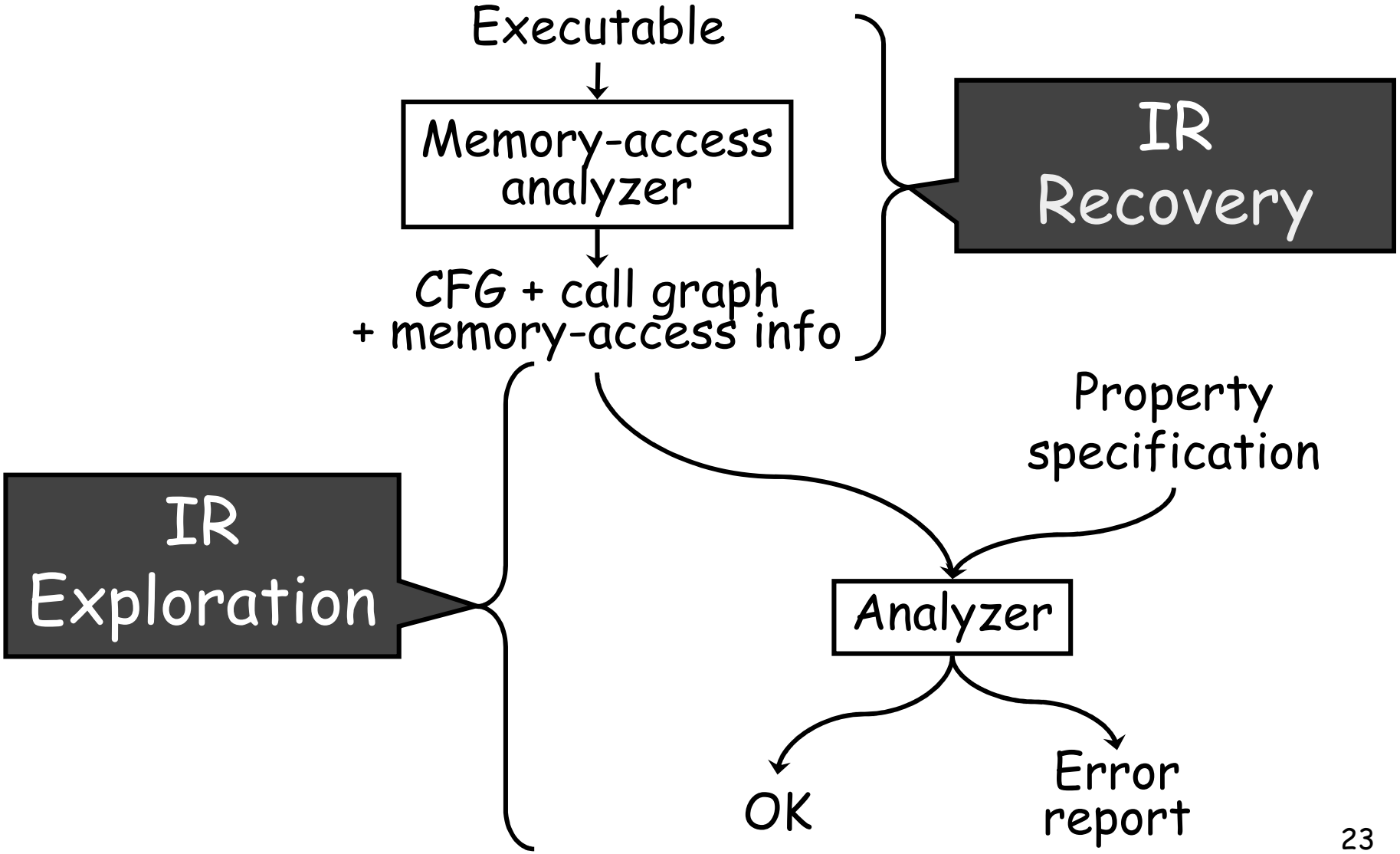

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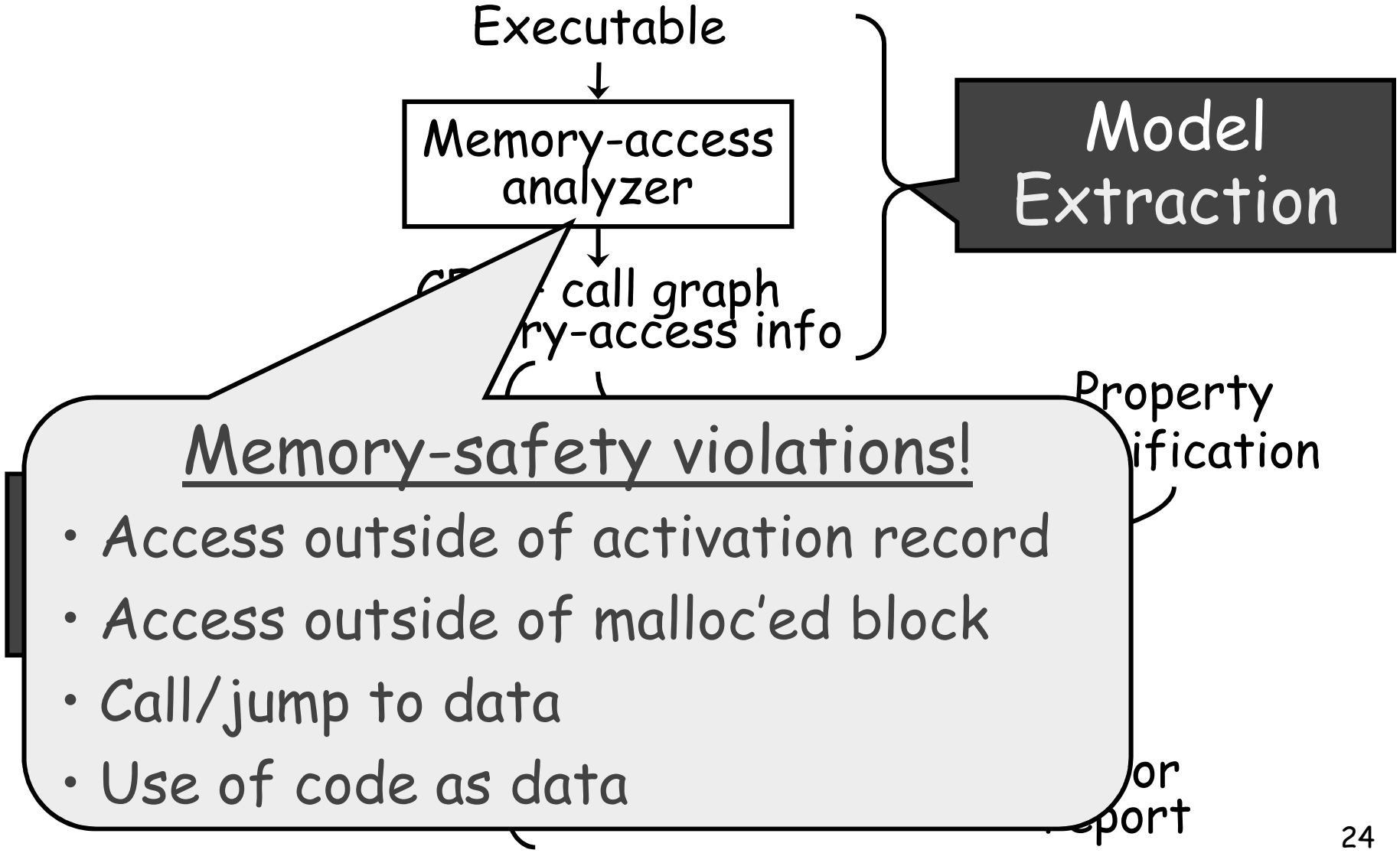


Our Approach

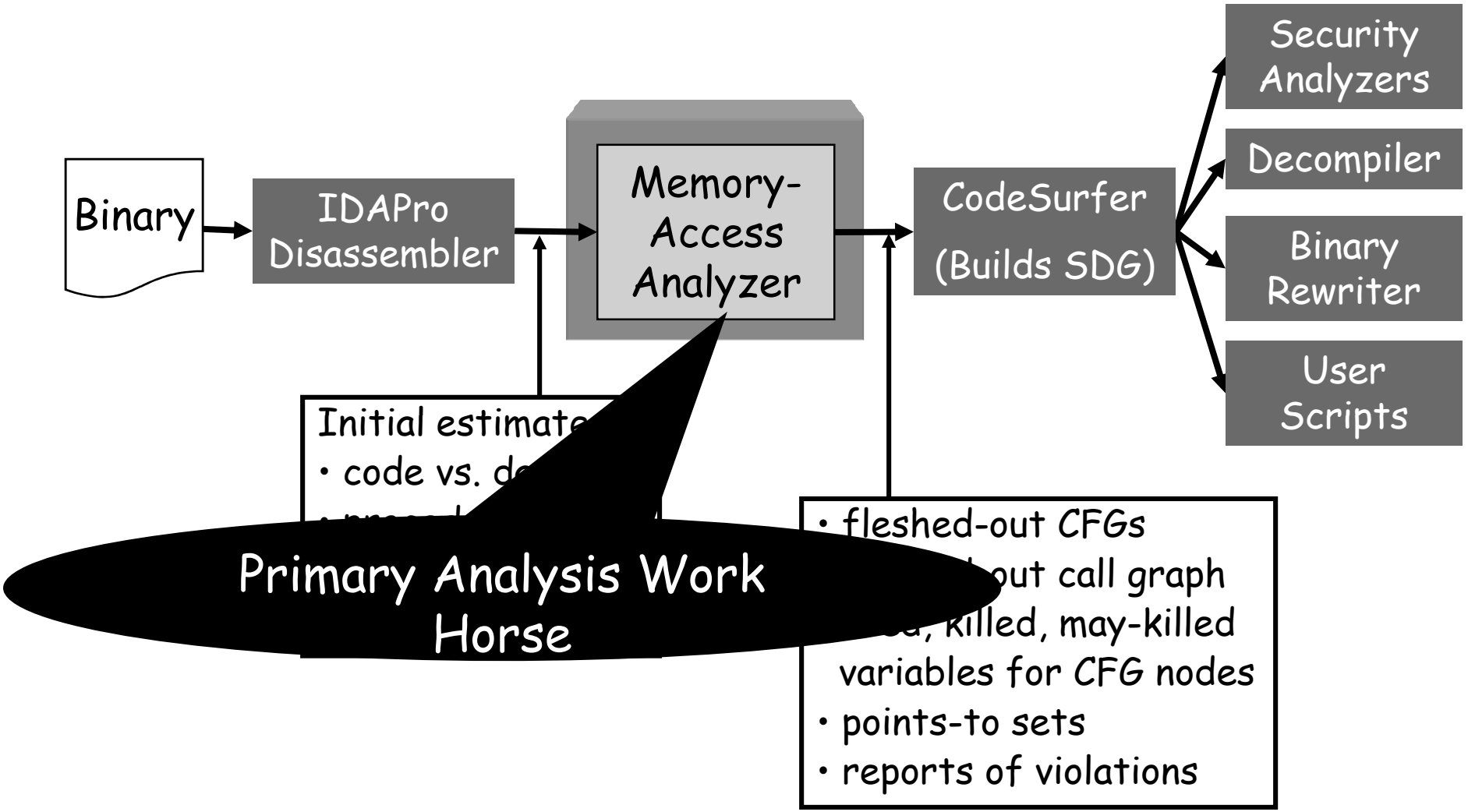
- Recover an Intermediate Representation (IR) from the executable
  - IR similar to that built by a compiler
    - control-flow graphs
    - call graph
    - set of variables
    - values of pointers
    - used, killed, and possibly-killed variables for CFG nodes
    - data dependences
    - types of variables: base types, pointer types, structs, and classes
- Use the recovered IR for further analysis
  - Finding bugs and security vulnerabilities
  - decompilation
  - . . .

Without Debugging Information!

Scope

- Programs that conform to a "standard compilation model"
  - procedures
  - activation records
  - global data region
  - heap, etc.
- Report violations
  - violations of stack protocol
  - return address modified within procedure

CodeSurfer/x86 Architecture



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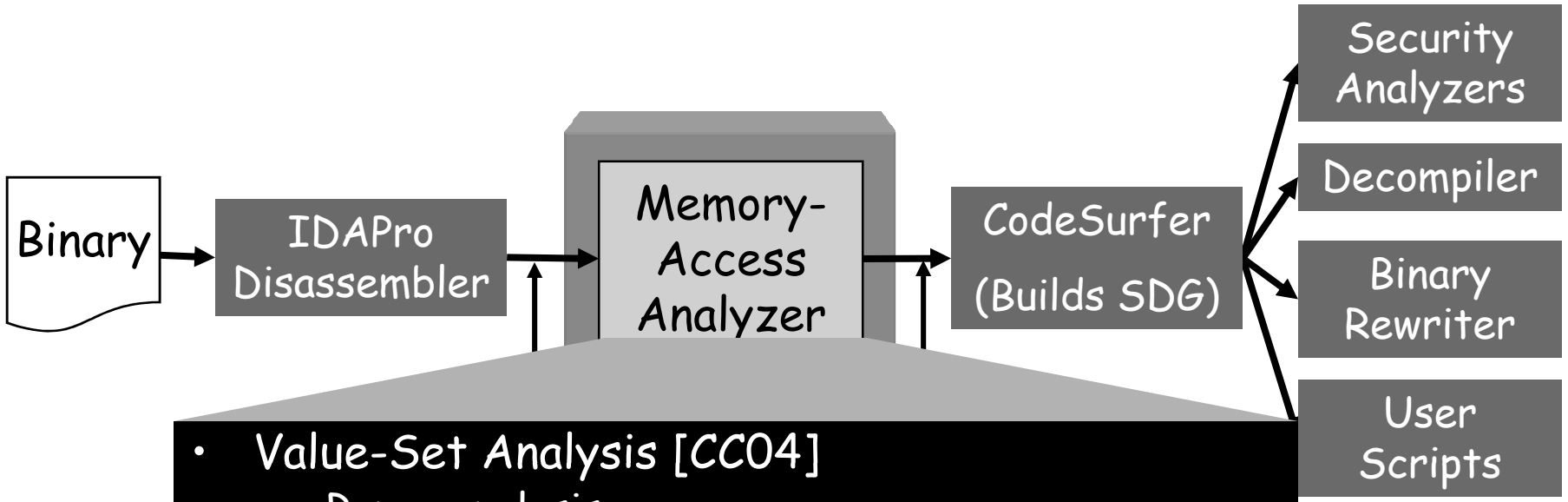

- Value-Set Analysis [CC04]
  - Range analysis
  - Pointer analysis
  - Indirect-jump & indirect-call resolution
  - Induction variables
- Variable recovery algorithm [VMCAI07]
  - Structure and Type recovery
- Analyzes heap-allocated data
  - Recency-abstraction [SAS06]

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Running Example

```
int arrVal=0, *pArray2;

int main() {
   int i, a[10], *p;
   /* Initialize pointers */
   pArray2 = &a[2];
   p = &a[0];
   /* Initialize Array */
   for(i = 0; i<10; ++i) {
      *p = arrVal;
      p++;
   }
   /* Return a[2] */
   return *pArray2;
}
```

```
; ebx ⇔ variable i
; ecx ⇔ variable p

sub    esp, 40        ;adjust stack
lea    edx, [esp+8]   ;
mov    [8], edx       ;pArray2=&a[2]
lea    ecx, [esp]     ;p=&a[0]
mov    edx, [4]       ;

loc_9:
   mov    [ecx], edx  ;*p=arrVal
   add    ecx, 4      ;p++
   inc    ebx         ;i++
   cmp    ebx, 10     ;i<10?
   jl     short loc_9 ;

mov    edi, [8]     ;
mov    eax, [edi]   ;return *pArray2
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retn
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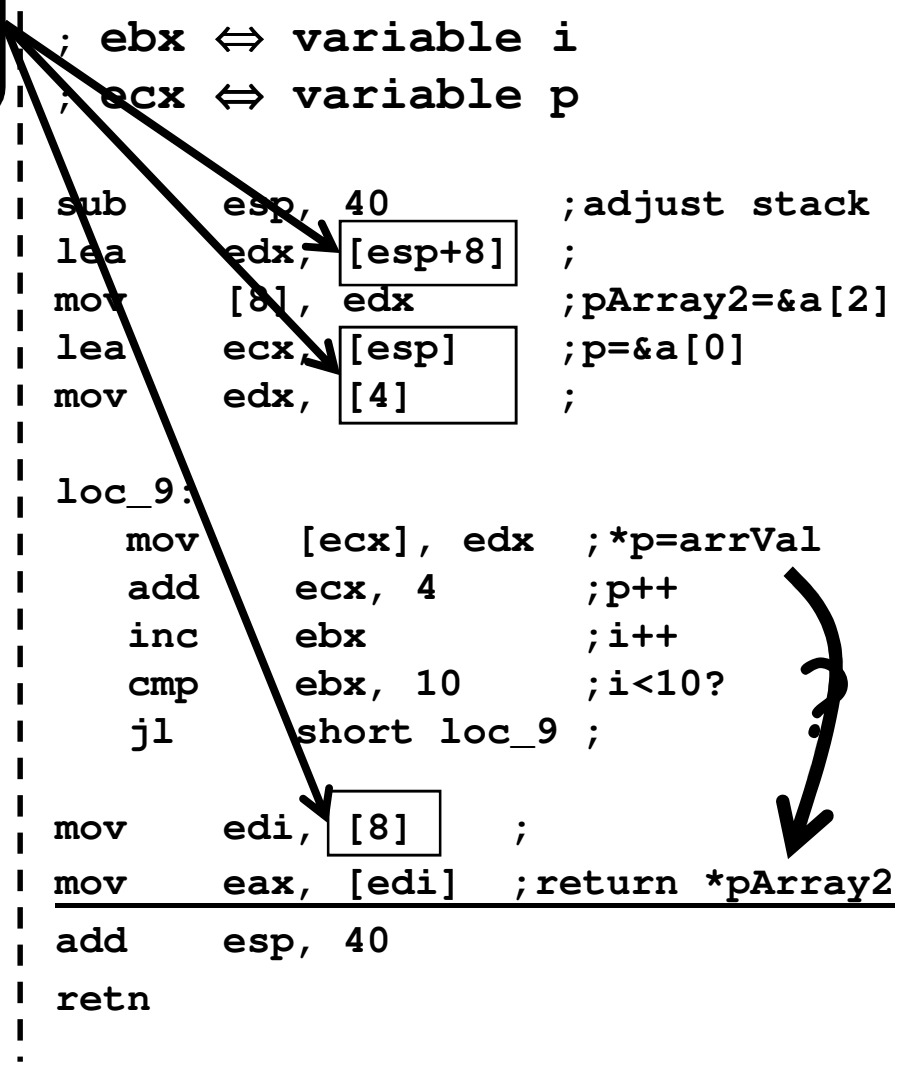
Challenges

No debugging information
(Unavailable/Unreliable)



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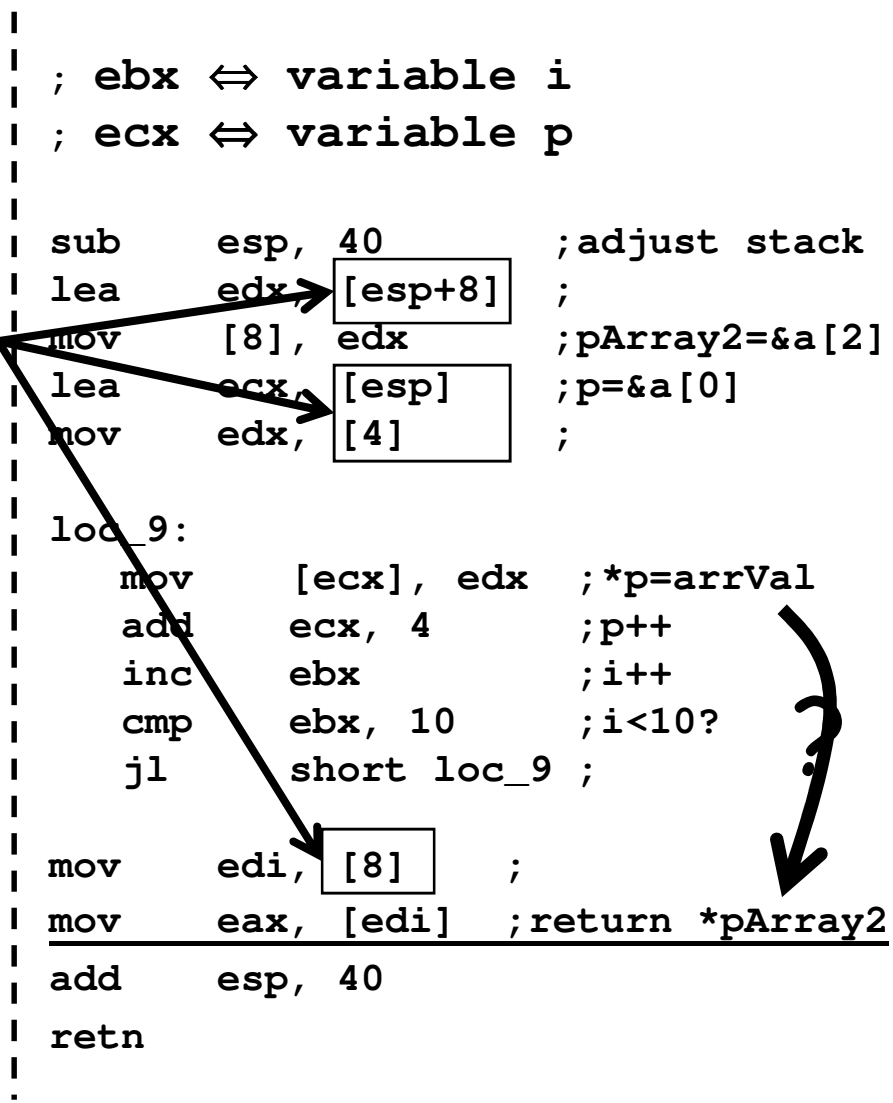
Challenges

No debugging information (Unavailable/Unreliable)

No notion of variables (Explicit memory addresses/offsets)



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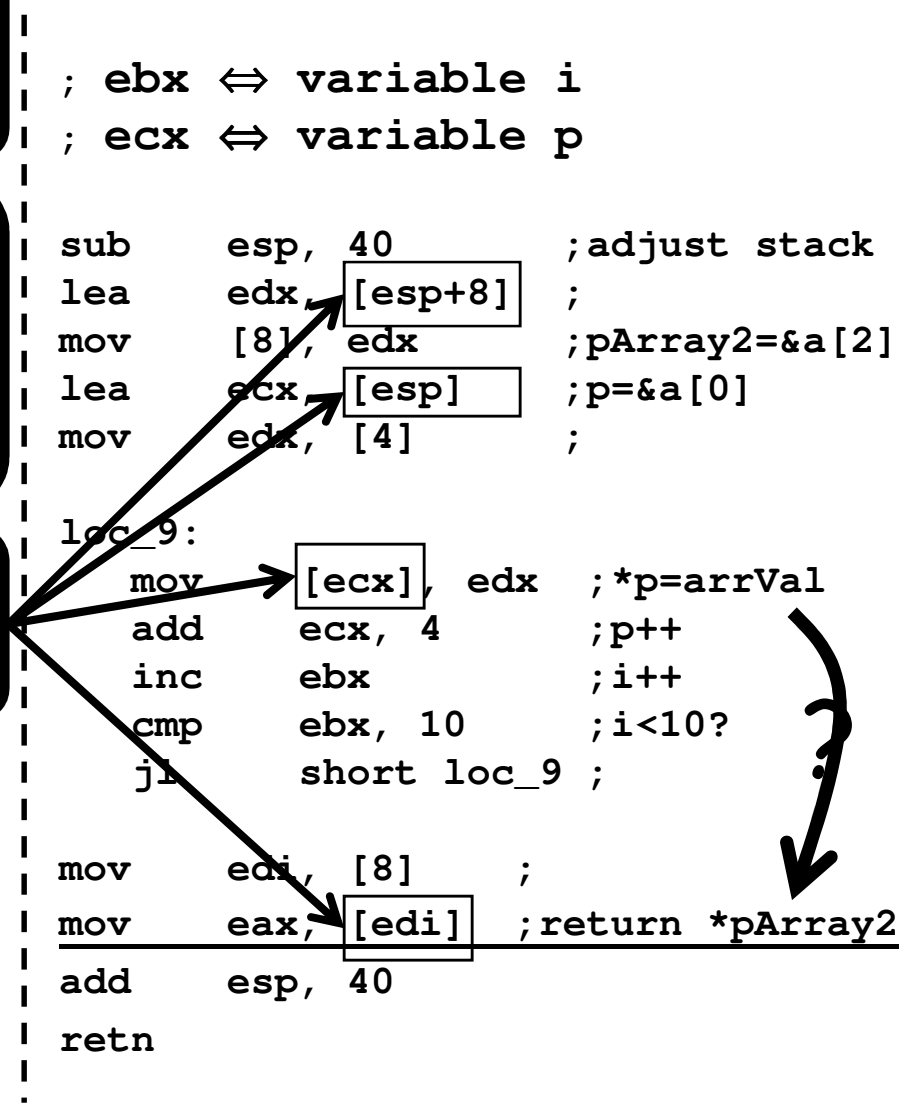
Indirect Addressing (Need Pointer Analysis)



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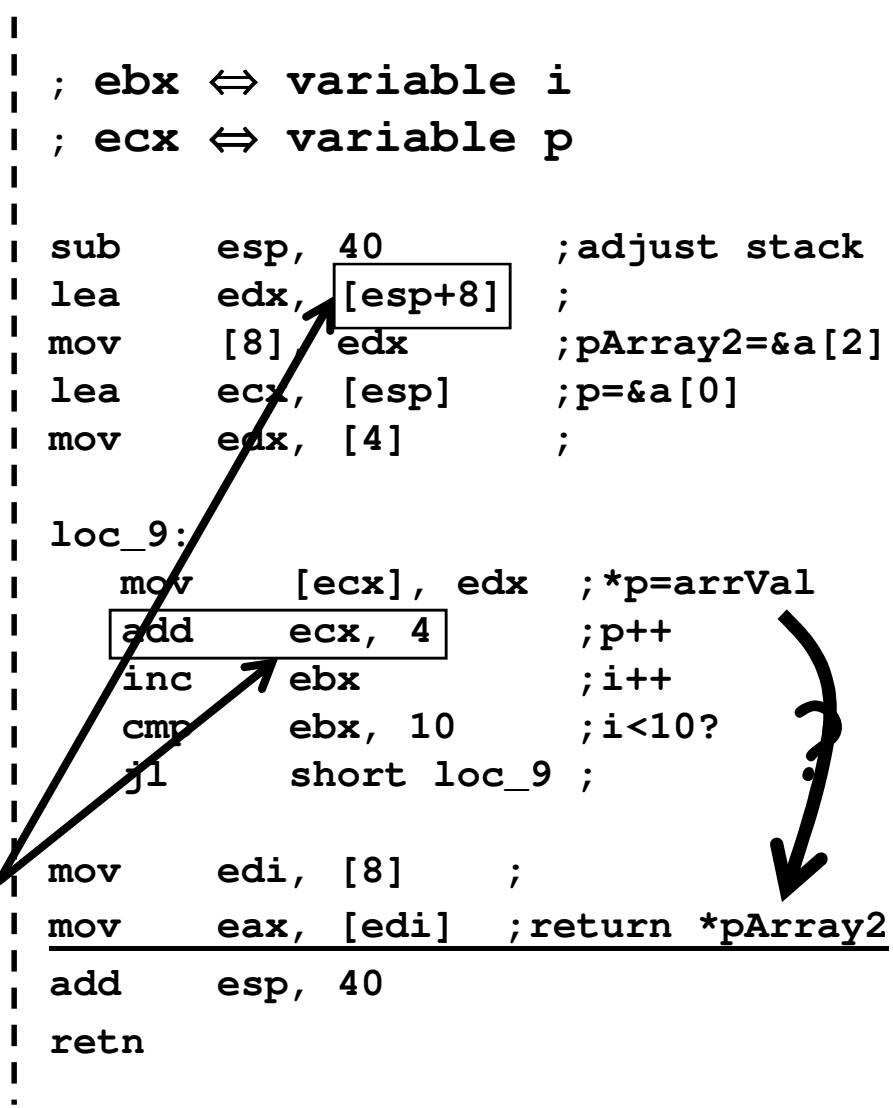
Indirect Addressing (Need Pointer Analysis)

Pointer Arithmetic (Need Numeric Analysis e.g., "Range Analysis")



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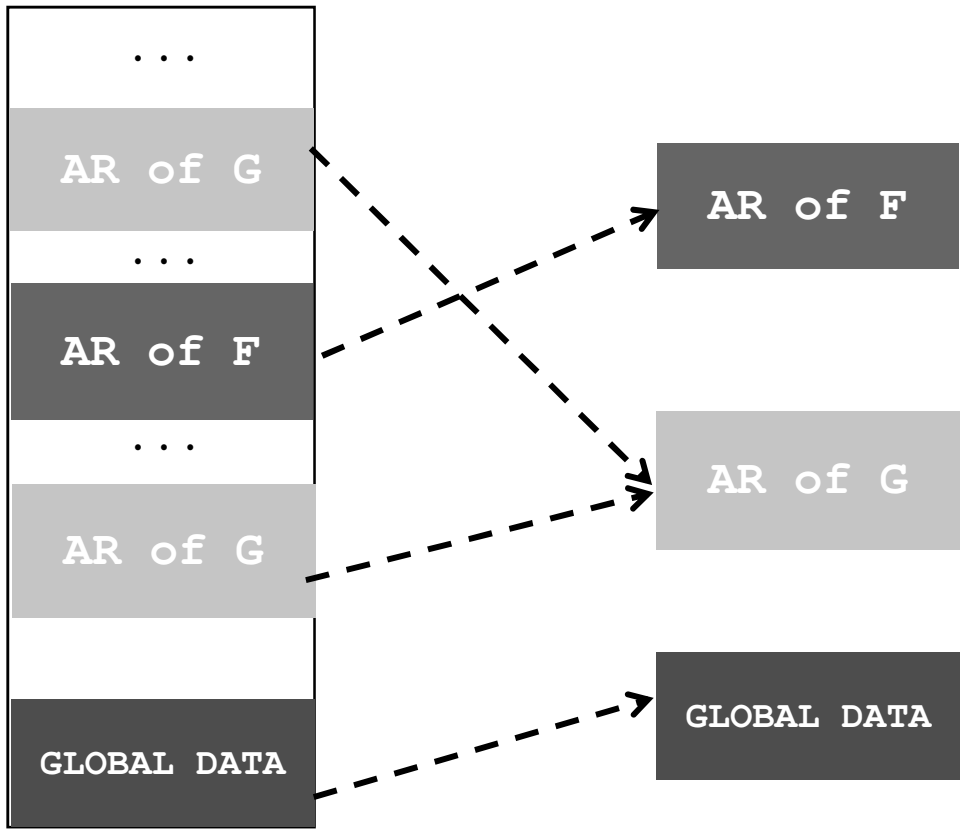
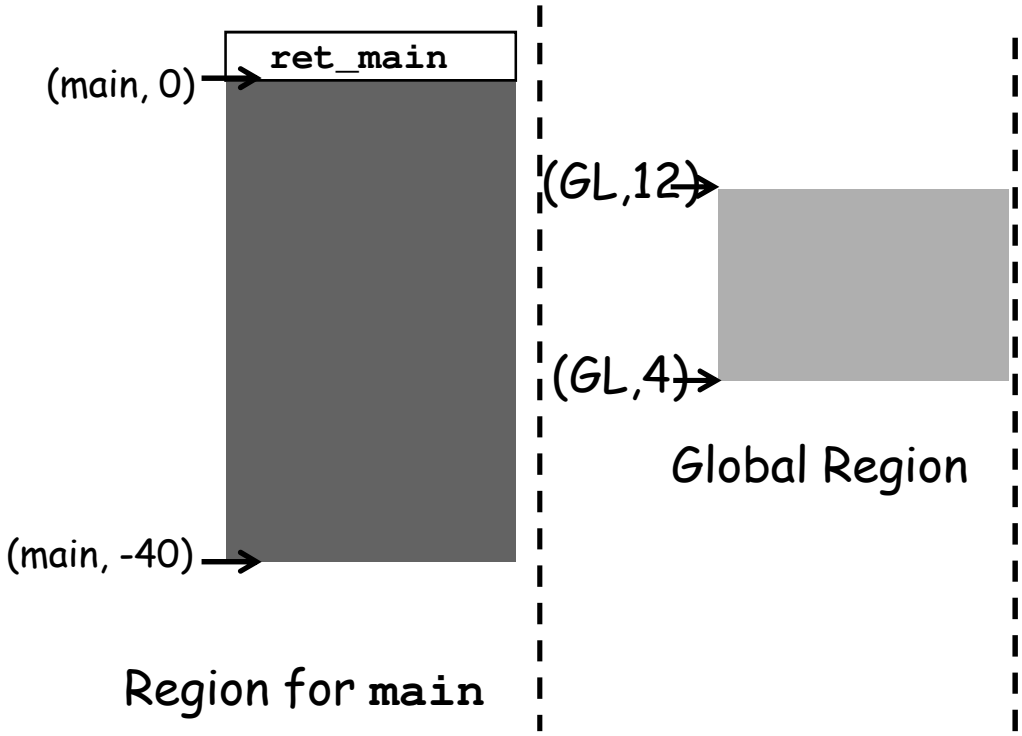
Memory-Regions

- A memory-region: a sequence of similar runtime addresses
  - AR-region: Addresses that belong to an activation record
  - Malloc-region: Addresses that are allocated at a malloc site
  - Global-region: Addresses that correspond to global data



Example - Memory Regions

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mov     edi, [8]     ;
mov     eax, [edi]   ;return *pArray2
add     esp, 40
retn
```

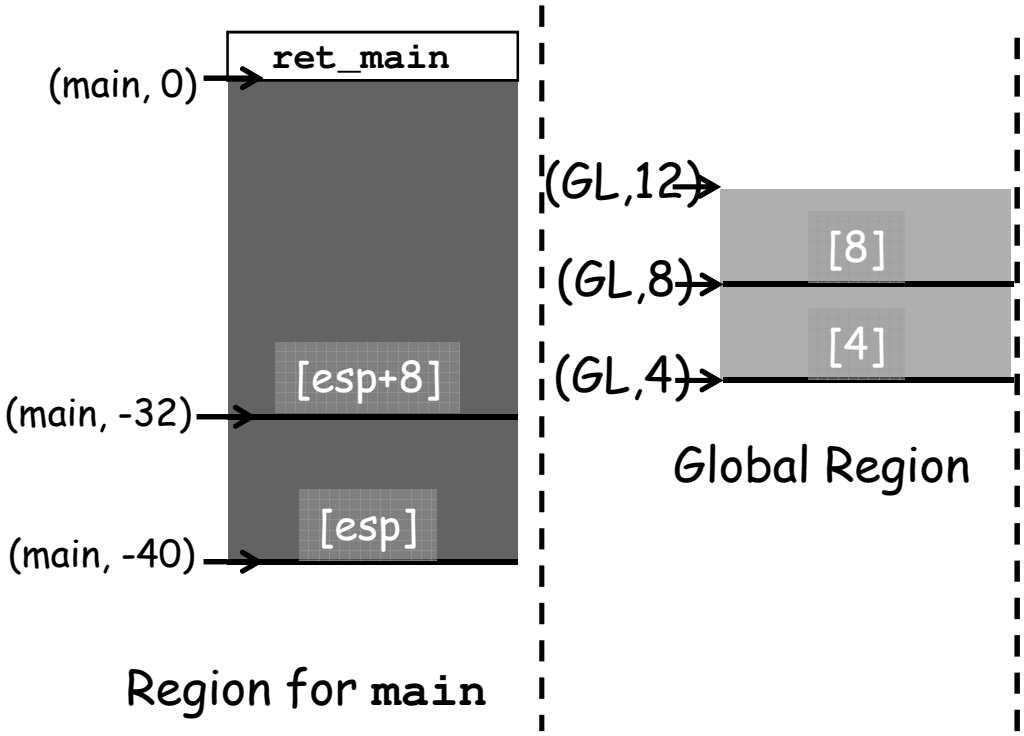
Recovering Variable-like Entities (a-loc)

- Data-layout known at assembly/compile time
  - some variables held in registers
  - global variables → absolute addresses
  - local variables → offsets in stack frame

- A-locs (for "Abstract-Locations")
  - locations between consecutive addresses
  - locations between consecutive offsets
  - Registers

- Referred to as the "Semi-Naïve algorithm"

Example: Variable-like Entities

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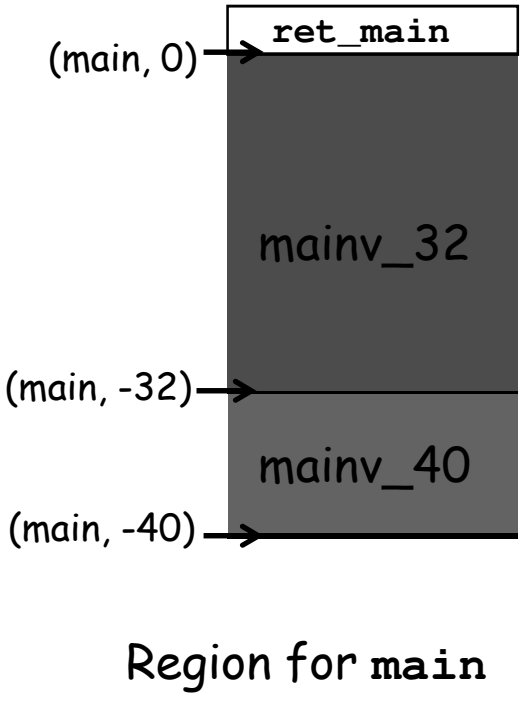

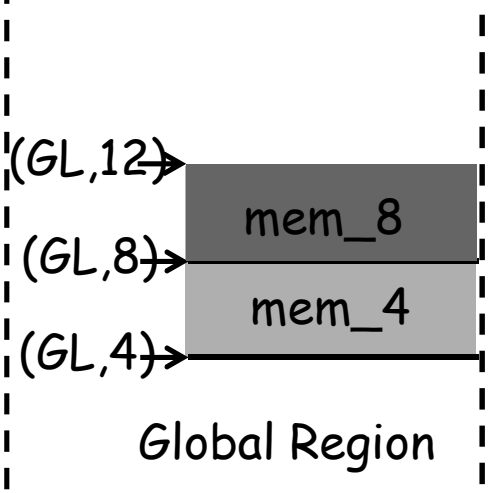


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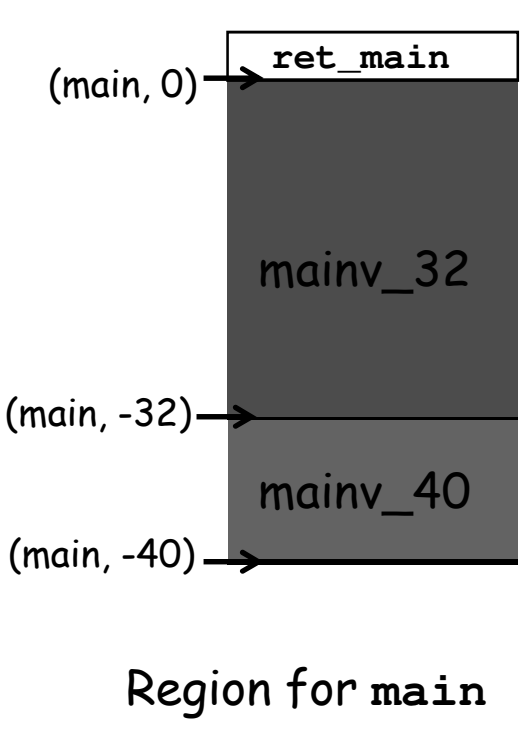

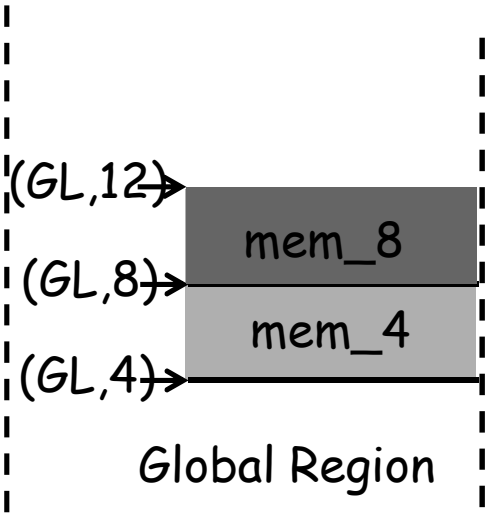


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sub     esp, 40          ;adjust stack
lea     edx, &mainv_32;
mov     mem_8, edx       ;pArray2=&a[2]
lea     ecx, &mainv_40;p=&a[0]
mov     edx, mem_4       ;

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Example: Standard Pointer Analysis?

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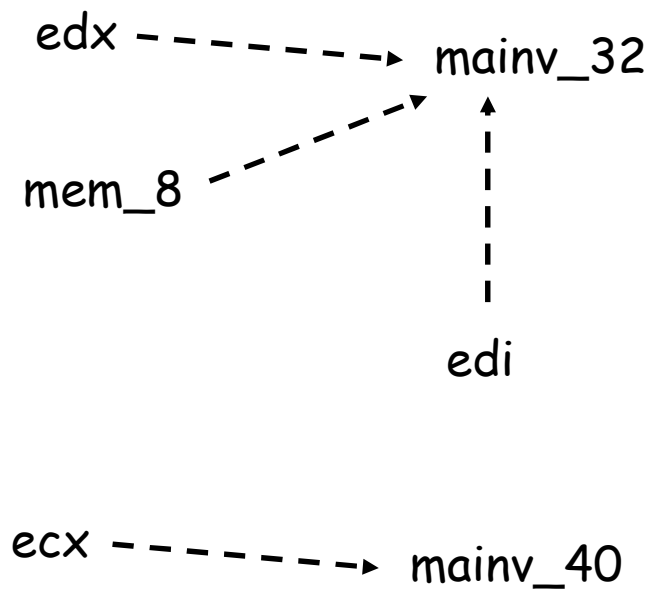
{a[0..1], a[2..9]}
globals: mem_4, mem_8
{arrVal, pArray2}

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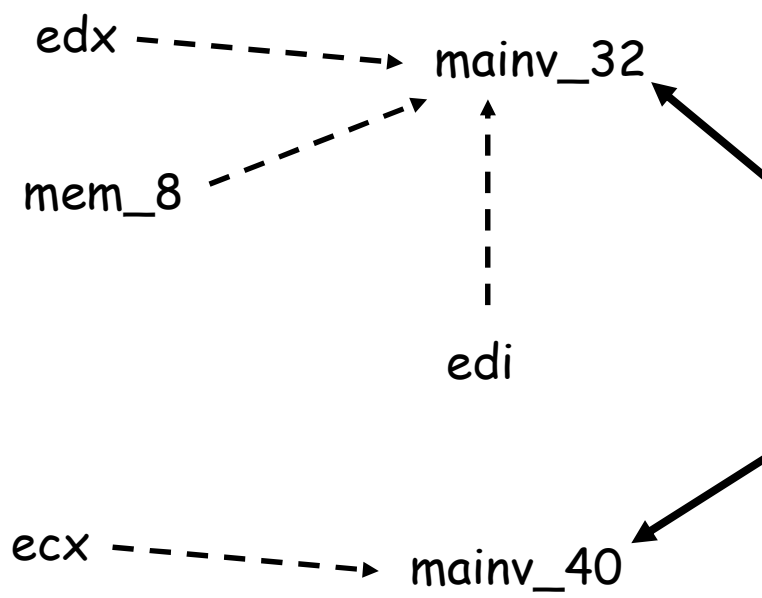
globals: mem_4, mem_8
{arrVal, pArray2}




```
; ebx ⇔ variable i
; ecx ⇔ variable p

sub     esp, 40         ;adjust stack
lea     edx, &mainv_32;
mov     mem_8, edx      ;pArray2=&a[2]
lea     ecx, &mainv_40;p=&a[0]
mov     edx, mem_4      ;

loc_9:
   mov     [ecx], edx   ;*p=arrVal
   add     ecx, 4       ;p++
   inc     ebx          ;i++
   cmp     ebx, 10      ;i<10?
   jl      short loc_9 ;

mov     edi, mem_8      ;
mov     eax, [edi]   ;return *pArray2
add     esp, 40
retn
```

Outline

- CodeSurfer/x86 architecture
- Challenges
- Core Analysis Algorithms
  - Recovering variable-like entities (a-loc)
  - Value-set Analysis (VSA)
  - Other Algorithms
- Device-Driver Analysis
  - Improved a-loc recovery

- What Next?

Value-set Analysis [CC04]

- For each a-loc, at every program point
  - Find the set of addresses/values held by the a-loc
  - Based on Abstract Interpretation
  - Abstract domain: value-set

- Resembles a pointer-analysis algorithm
  - Over-approximation for the set of addresses
  - Interprets pointer-manipulation operations
  - Pointer arithmetic, too

- Resembles a numeric-analysis algorithm
  - Over-approximation for the set of values

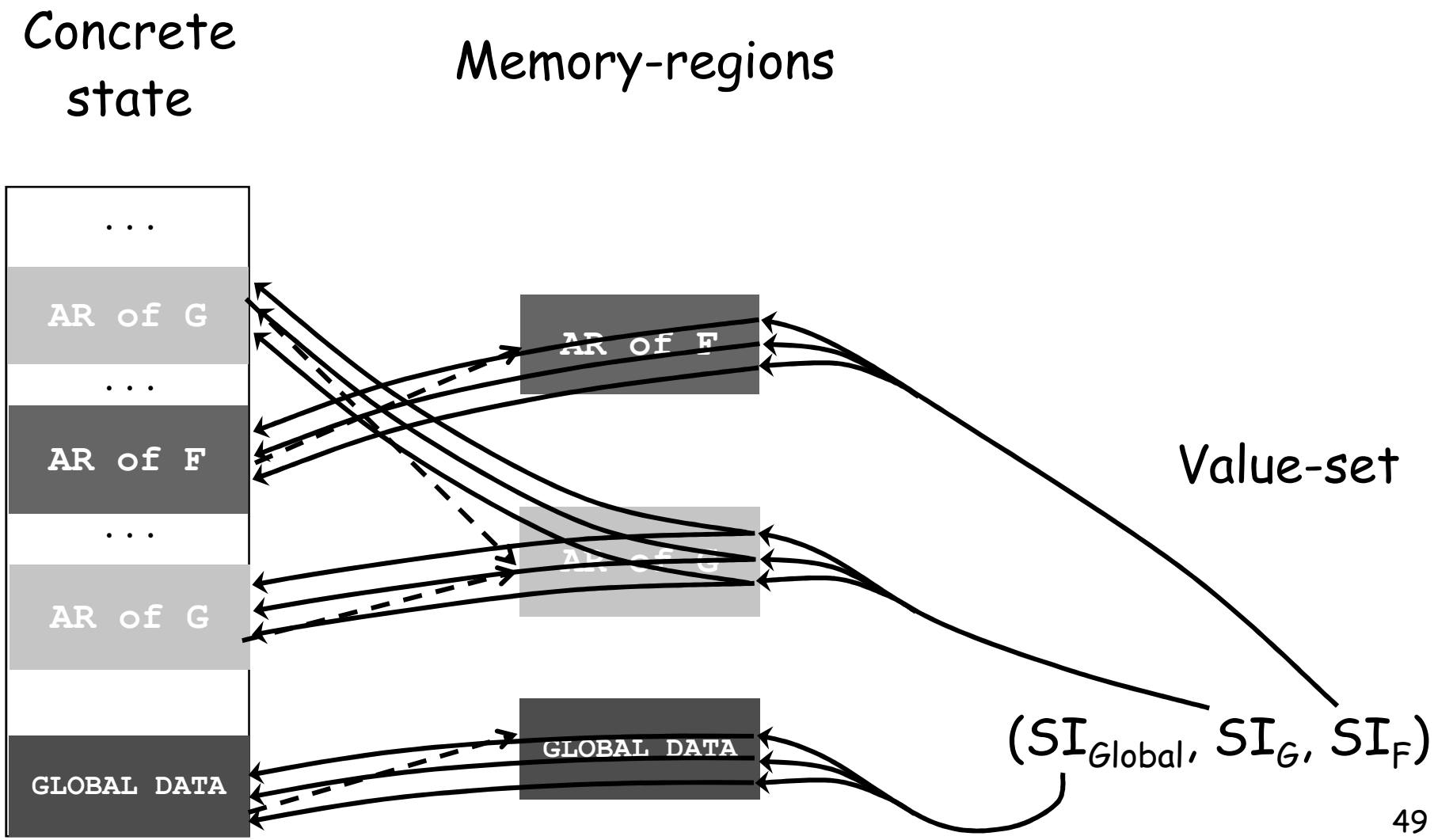
Value-set [PEPM06]

- A representation for a set of addresses/values

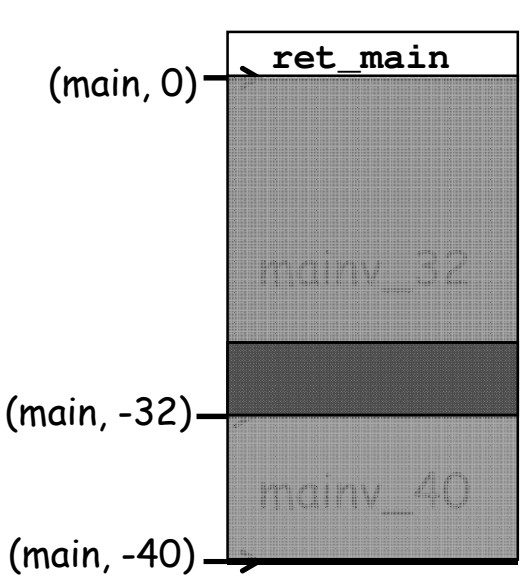
- Strided-Interval (SI)
  - represents a set of values
  - records a range and a stride
  - {1, 3, 5, 9} represented as 2[1,9]
  - conservative: 2[1,9] represents {1, 3, 5, 7, 9}

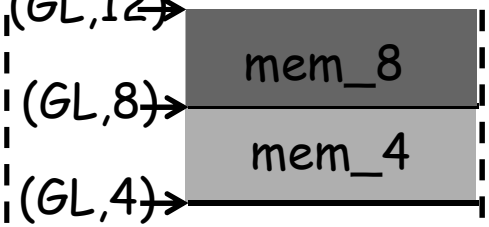
- Value-set
  - r-tuple of SIs: (si_1, . . ., si_r)
  - i^{th} component — offsets in i^{th} memory-region
  - si_1 – offsets in global region
  - (si_1, Ø, . . ., Ø) – set of numbers

Value-Set:
A Set of Abstract Addresses and Values



Example - Value-set analysis





Global Region

Region for **main**

1 **ecx** → (Ø , 4[-40,-4])
ebx → (1[0,9] , Ø)

2 **edi** → (Ø, -32)

```
; ebx ⇔ variable i
; ecx ⇔ variable p

sub     esp, 40         ;adjust stack
lea     edx, [esp+8]    ;
mov     [8], edx        ;pArray2=&a[2]
lea     ecx, [esp]      ;p=&a[0]
mov     edx, [4]        ;

loc_9:
   mov     [ecx], edx   ;*p=arrVal   1
   add     ecx, 4       ;p++
   inc     ebx          ;i++
   cmp     ebx, 10      ;i<10?
   jl      short loc_9  ;

mov     edi, [8]     ;
mov     eax, [edi]   ;return *pArr   2
add     esp, 40
retn
```

Outline

- CodeSurfer/x86 architecture
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  - Other Algorithms
- Device-Driver Analysis
  - Improved a-loc recovery

- What Next?

Static-Analysis Algorithms in CodeSurfer/x86

- Value-Set Analysis [CC04]
- Improved Aloc-Recovery Algorithm [VMCAI07]
- Recency-Abstraction For Heap-Allocated Storage [SAS06]
- Affine-Relation Analysis (ARA) [CC04, CAV05]

- Path-Sensitive VSA [TACAS08]
- Improvements to VSA
  - GMOD-based merge function [CC08]
  - Priority-based iteration
  - Improved widening with Bourdoncle components
- Windows Device-driver Analysis [TACAS08]

Outline

- CodeSurfer/x86 architecture
- Challenges
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  - Other Algorithms
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  - Improved a-loc recovery

- What Next?

Device-Driver Analysis

- Device Driver
  - like a library that exports procedures
  - each procedure: actions for an I/O request
    - e.g., `AddDevice` routine
      - invoked by OS when a new device is added
    - referred to as "dispatch routines"

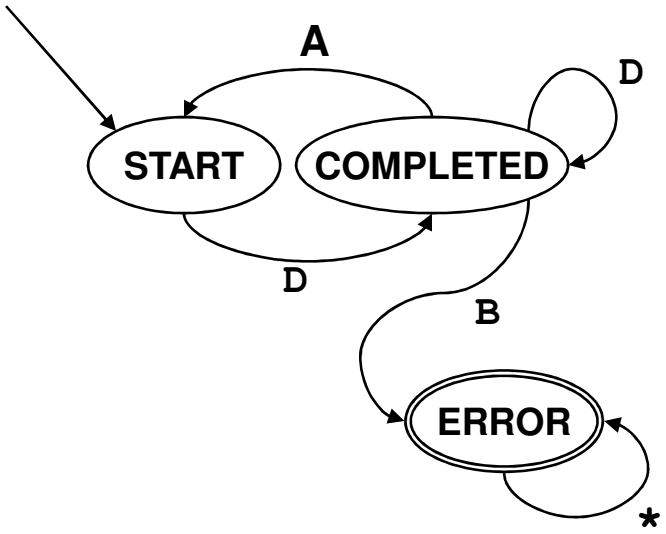
- Windows Kernel API is complex
  - 85% of crashes in Windows due to driver bugs
    - [Swift et al. 2005]

Device Driver Analysis

". . . You must examine the object code to be sure it matches your expectations, or at least will work correctly in the kernel environment. . ."

(From a document on Microsoft's WHDC website)

PendedCompletedRequested Rule (simplified version)



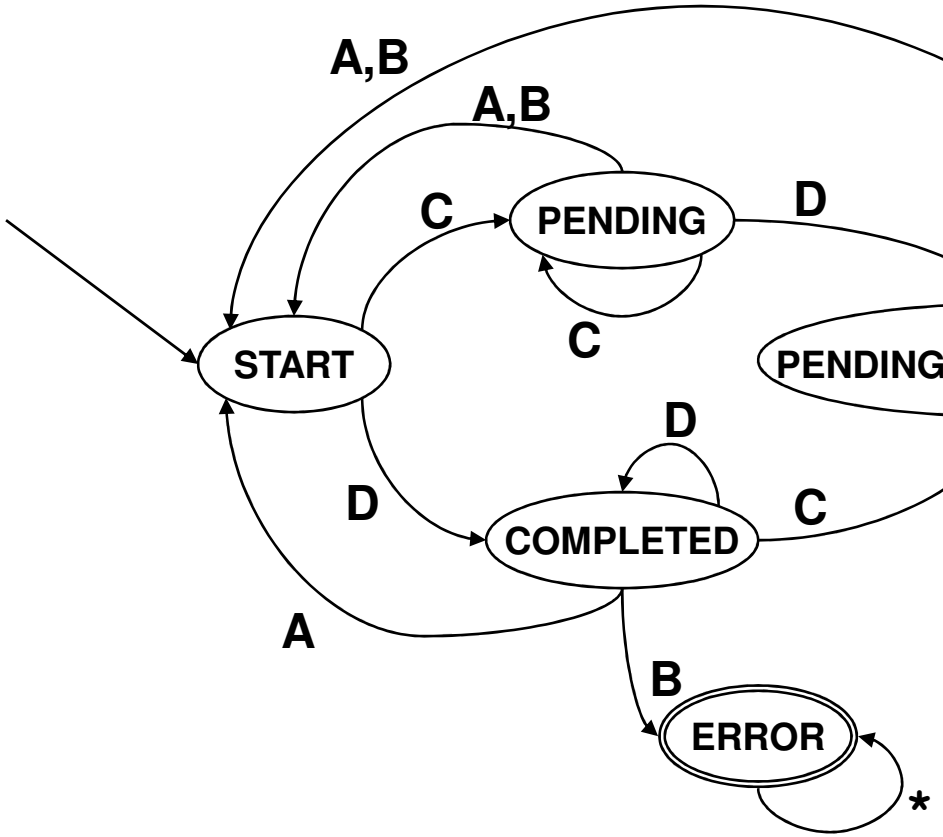
A: `return value ≠ STATUS_PENDING`

B: `return value = STATUS_PENDING`

D: `IoCompleteRequest`

"A driver's dispatch routine does not return **`STATUS_PENDING`** on an I/O Request Packet (IRP) if it has called ***`IoCompleteRequest`*** on the IRP."

PendedCompletedRequested Rule



A: `"return status ≠ STATUS_PENDING"`

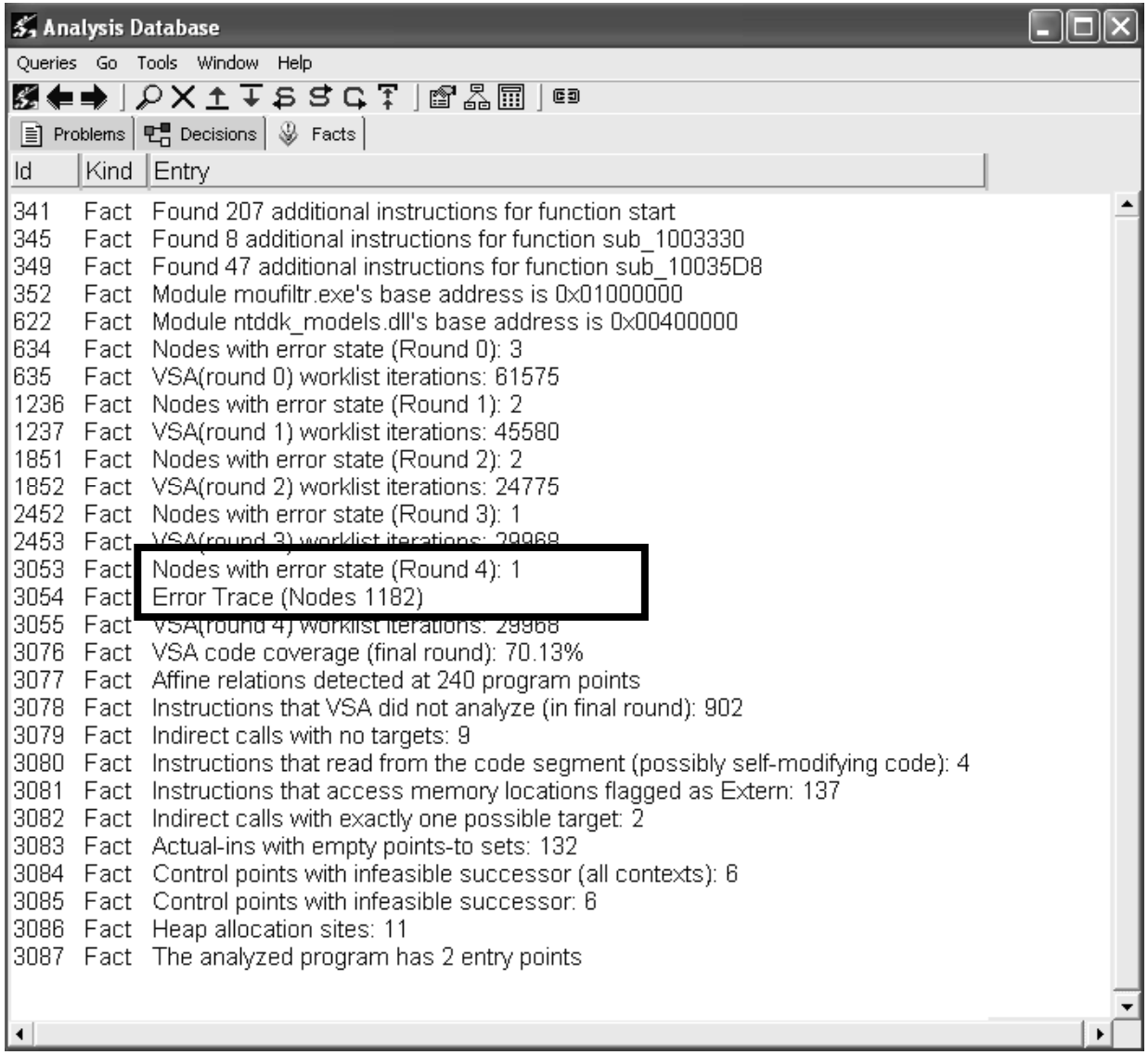
B: `"return status = STATUS_PENDING"`

C: ***`IoMarkPending`***

D: ***`IoCompleteRequest`***

"A driver's dispatch routine does not return **`STATUS_PENDING`** on an I/O Request Packet (IRP) if it has called ***`IoCompleteRequest`*** on the IRP, unless it has also called ***`IoMarkIrpPending`***."

CS/x86: Device Driver Analysis



SLAM Error Trace

```
KeInitializeEvent(&event,
                  NotificationEvent,
                  FALSE
                  );

IoSetCompletionRoutine(Irp,
                       (PIO_COMPLETION_ROUTINE) MouFilter_Complete,
                       &event,
                       TRUE,
                       TRUE,
                       TRUE); // No need for Cancel

status = IoCallDriver(devExt->TopOfStack, Irp);

if (STATUS_PENDING == status) {
    KeWaitForSingleObject(
       &event,
       Executive, // Waiting for reason of a driver
       KernelMode, // Waiting in kernel mode
       FALSE, // No allert
       NULL); // No timeout
}

if (NT_SUCCESS(status) && NT_SUCCESS(Irp->IoStatus.Status)) {
    //
    // As we are successfully now back from our start device
    // we can do work.
    //
    devExt->Started = TRUE;
    devExt->Removed = FALSE;
    devExt->SurpriseRemoved = FALSE;
}

//
// We must now complete the IRP, since we stopped it in the
// completetion routine with MORE_PROCESSING_REQUIRED.
//
Irp->IoStatus.Status = status;
Irp->IoStatus.Information = 0;
IoCompleteRequest(Irp, IO_NO_INCREMENT);

break;
}
```

DDA/x86 Error Trace

```
push    1
push    1
push    1
lea     ecx, dword ptr [ebp + var_1C]
push    ecx
push    sub_1002270
mov     edx, dword ptr [ebp + arg_4]
push    edx
call    dword ptr [_sdv_IoSetCompletionRoutine@24]
mov     edx, dword ptr [ebp + arg_4]
mov     eax, dword ptr [ebp + var_4]
mov     ecx, dword ptr [eax + 8]
call    dword ptr [@IofCallDriver@8]
mov     dword ptr [ebp + var_20], eax
cmp     dword ptr [ebp + var_20], 103h
jnz     loc_10013E1
push    0
push    0
push    0
push    0
lea     ecx, dword ptr [ebp + var_1C]
push    ecx
call    dword ptr [_sdv_KeWaitForSingleObject@20]

loc_10013E1:
cmp     dword ptr [ebp + var_20], 0
jl      loc_1001405
mov     edx, dword ptr [ebp + arg_4]
cmp     dword ptr [edx + 18h], 0
jl      loc_1001405
mov     eax, dword ptr [ebp + var_4]
mov     byte ptr [eax + 30h], 1
mov     ecx, dword ptr [ebp + var_4]
mov     byte ptr [ecx + 32h], 0
mov     edx, dword ptr [ebp + var_4]
mov     byte ptr [edx + 31h], 0

loc_1001405:
mov     eax, dword ptr [ebp + arg_4]
mov     ecx, dword ptr [ebp + var_20]
mov     dword ptr [eax + 18h], ecx
mov     edx, dword ptr [ebp + arg_4]
mov     dword ptr [edx + 1Ch], 0
push    0
mov     eax, dword ptr [ebp + arg_4]
push    eax
call    dword ptr [_sdv_IoCompleteRequest@8]
jmp     loc_10014B0

loc_1001429:
```

SLAM Error Trace

```
status = IoCallDriver(devExt->TopOfStack, Irp);

if (STATUS_PENDING == status) {
    KeWaitForSingleObject(
        &event,
        Executive, // Waiting for reason of a driver
        KernelMode, // Waiting in kernel mode
        FALSE, // No allert
        NULL); // No timeout
}
```

DDA/x86 Error Trace

```
mov     edx, dword ptr [ebp + arg_4]
mov     eax, dword ptr [ebp + var_4]
mov     ecx, dword ptr [eax + 8]
call    dword ptr [@IofCallDriver@8]
mov     dword ptr [ebp + var_20], eax
cmp     dword ptr [ebp + var_20], 103h
jnz     loc_10013E1
push    0
push    0
push    0
push    0
lea     ecx, dword ptr [ebp + var_1C]
push    ecx
call    dword ptr [_sdv_KeWaitForSingleObject@20]
```

SLAM Error Trace

```
if (NT_SUCCESS(status) && NT_SUCCESS(Irp->IoStatus.Status)) {
    //
    // As we are successfully now back from our start device
    // we can do work.
    //
    devExt->Started = TRUE;
    devExt->Removed = FALSE;
    devExt->SurpriseRemoved = FALSE;
}
```

DDA/x86 Error Trace

```
loc_10013E1:
    cmp     dword ptr [ebp + var_20], 0
    jl      loc_1001405
    mov     edx, dword ptr [ebp + arg_4]
    cmp     dword ptr [edx + 18h], 0
    jl      loc_1001405
    mov     eax, dword ptr [ebp + var_4]
    mov     byte ptr [eax + 30h], 1
    mov     ecx, dword ptr [ebp + var_4]
    mov     byte ptr [ecx + 32h], 0
    mov     edx, dword ptr [ebp + var_4]
    mov     byte ptr [edx + 31h], 0
```

SLAM Error Trace

```
//
// We must now complete the IRP, since we stopped it in the
// completetion routine with MORE_PROCESSING_REQUIRED.
//
Irp->IoStatus.Status = status;
Irp->IoStatus.Information = 0;
IoCompleteRequest(Irp, IO_NO_INCREMENT);

break;
```

DDA/x86 Error Trace

```
loc_1001405:
    mov     eax, dword ptr [ebp + arg_4]
    mov     ecx, dword ptr [ebp + var_20]
    mov     dword ptr [eax + 18h], ecx
    mov     edx, dword ptr [ebp + arg_4]
    mov     dword ptr [edx + 1Ch], 0
    push    0
    mov     eax, dword ptr [ebp + arg_4]
    push    eax
    call    dword ptr [_sdv_IoCompleteRequest@8]
    jmp     loc_10014B0
```

Results For *PendedCompletedRequested* Rule

Driver	Procedures	Instructions	⊖ Result	⊖ Feasible Trace?	⊛ reported by Result	⊛ Feasible Trace?	◎ Result	◎ Feasible Trace?	★ Result	★ Feasible Trace?
src/vdd/dosioctl/krnldrvr	70	2824	FP	-	√	-	√	-	√	-
src/general/ioctl/sys	76	3504	FP	-	√	-	√	-	√	-
src/general/tracedrv/tracedrv	84	3719	FP	-	√	-	√	-	√	-
src/general/cancel/startio	96	3861	FP	-	FP	-	√	-	√	-
src/general/cancel/sys	102	4045	FP	-	√	-	√	-	√	-
src/input/moufiltr	93	4175	×	No	×	No	×	No	×	Yes
src/general/event/sys	99	4215	FP	-	√	-	√	-	√	-
src/input/kbfiltr	94	4228	×	No	×	No	×	No	×	Yes
src/general/toaster/toas2tmon	123	6261	FP	-	FP	-	FP	-	√	-
src/storage/filters/diskperf	121	6584	FP	-	FP	-	FP	-	√	-
src/network/modem/fakemodem	142	8747	FP	-	FP	-	FP	-	√	-
src/storage/fdc/flpydisk	171	12752	FP	-	FP	-	FP	-	FP	-
src/input/mouclass	192	13380	FP	-	FP	-	FP	-	FP	-
src/input/mouser	188	13989	FP	-	FP	-	FP	-	FP	-
src/kernel/serenum	184	14123	FP	-	FP	-	FP	-	√	-
src/wdm/1394/driver/1394diag	171	23430	FP	-	FP	-	FP	-	FP	-
src/wdm/1394/driver/1394vdev	173	23456	FP	-	FP	-	FP	-	FP	-

√: passes rule, ×: a real bug found, and FP: False positive.

⊖: A-locs from semi-naïve algorithm

⊛: No GMOD-based merge function

◎: With GMOD-based merge function

★: With cross-product automaton

Outline

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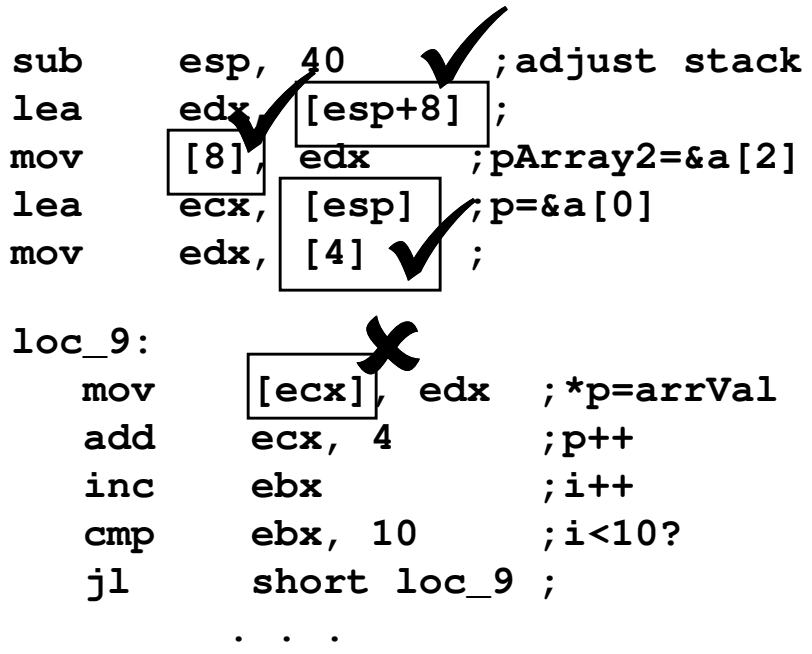
  - Improved a-loc recovery

- What Next?

Improved A-loc Identification [VMCAI07]

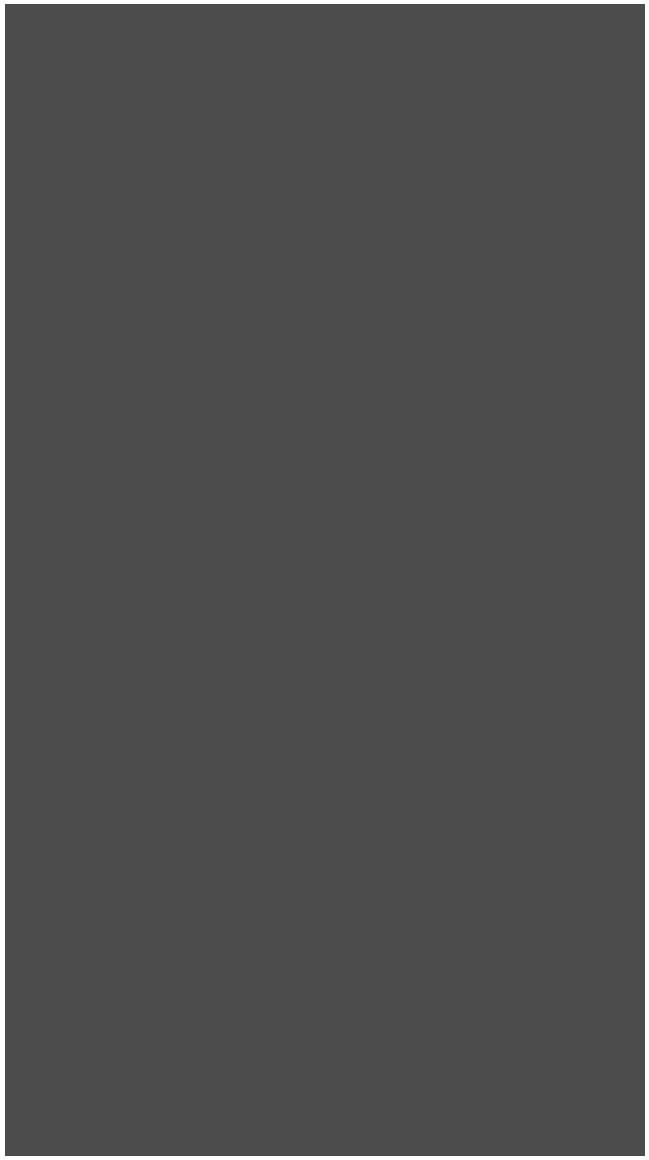
- A-locs from semi-naïve algorithm
  - Based only on explicitly specified addresses/offsets
  - Access based on indirect operands not taken into account



Device Extension Structure for "moufiltr" driver

PDEVICE_OBJECT
PDEVICE_OBJECT
PDEVICE_OBJECT
LONG
PVOID
PI8042_MOUSE_ISR
PI8042_ISR_WRITE_PORT
PVOID
PI8042_QUEUE_PACKET
CONNECT_DATA
DEVICE_POWER_STATE
BOOLEAN
BOOLEAN
BOOLEAN

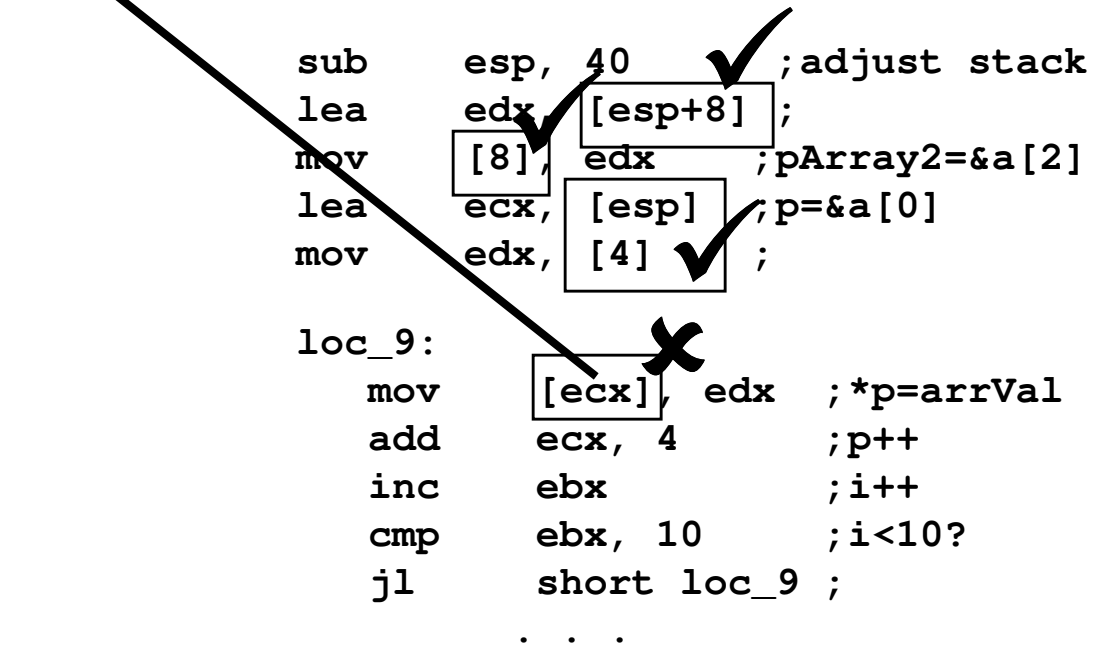
Declaration in C Source



Structure in Executable

Improved A-loc Identification [VMCAI07]

- A-locs from semi-naïve algorithm
  - Based only on explicitly specified addresses/offsets
  - Access based on indirect operands not taken into account
- VSA provides access patterns for indirect operands
  - **ecx** $\rightarrow$ (Ø, 4[-40,-4])
  - 4[0,9]-40 = {-40, -36, . . . , -4}

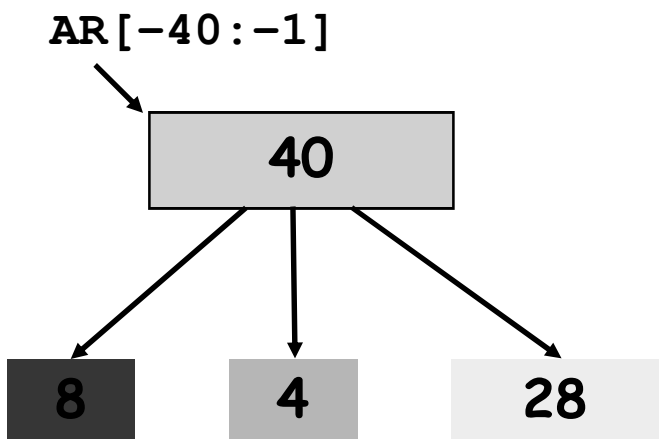


Improved A-loc Identification: VSA+ASI

- Aggregate Structure Identification (ASI)
  - Ramalingam et al. POPL99
  - Partition aggregates automatically
    - based on the program's memory-access patterns
  - Original motivation: Y2K

- ASI provides type information
  - Identifies structs and arrays
  - Propagates type information
    - from known parameter types
    - e.g., system calls & library functions

Aggregate Structure Identification



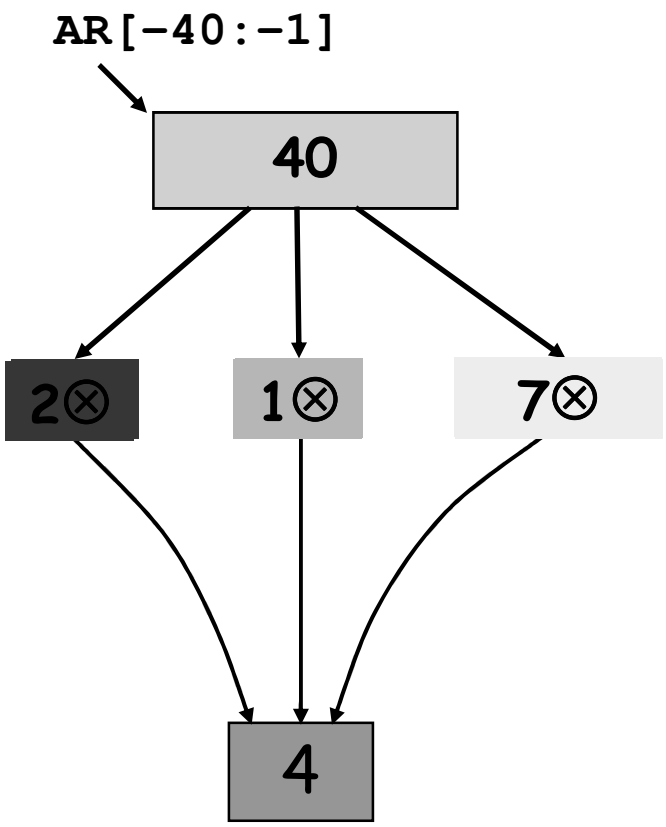

```
; ebx ⇔ variable i
; ecx ⇔ variable p

sub     esp, 40         ;adjust stack
lea     edx, [esp+8]    ;
mov     [4], edx        ;pArray2=&a[2]
lea     ecx, [esp]      ;p=&a[0]
mov     edx, [0]        ;

loc_9:
   mov     [ecx], edx   ;*p=arrVal
   add     ecx, 4       ;p++
   inc     ebx          ;i++
   cmp     ebx, 10      ;i<10?
   jl      short loc_9  ;

mov     edi, [4]     ;
mov     eax, [edi]   ;return *pArray2
add     esp, 40
retn
```

Aggregate Structure Identification




```
; ebx ⇔ variable i
; ecx ⇔ variable p

sub     esp, 40         ;adjust stack
lea     edx, [esp+8]    ;
mov     [4], edx        ;pArray2=&a[2]
lea     ecx, [esp]      ;p=&a[0]
mov     edx, [0]        ;

loc_9:
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   add     ecx, 4       ;p++
   inc     ebx          ;i++
   cmp     ebx, 10      ;i<10?
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mov     edi, [4]     ;
mov     eax, [edi]   ;return *pArray2
add     esp, 40
retn
```
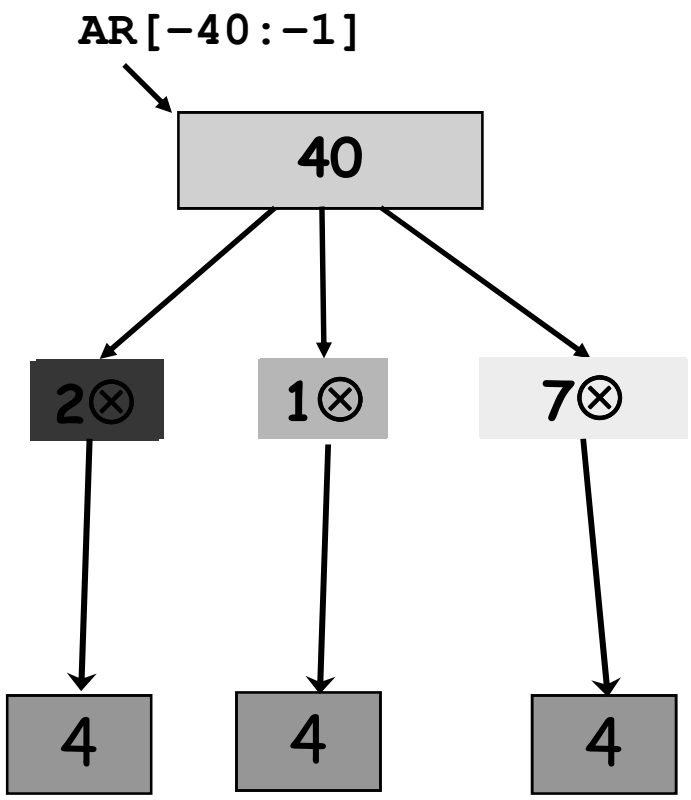
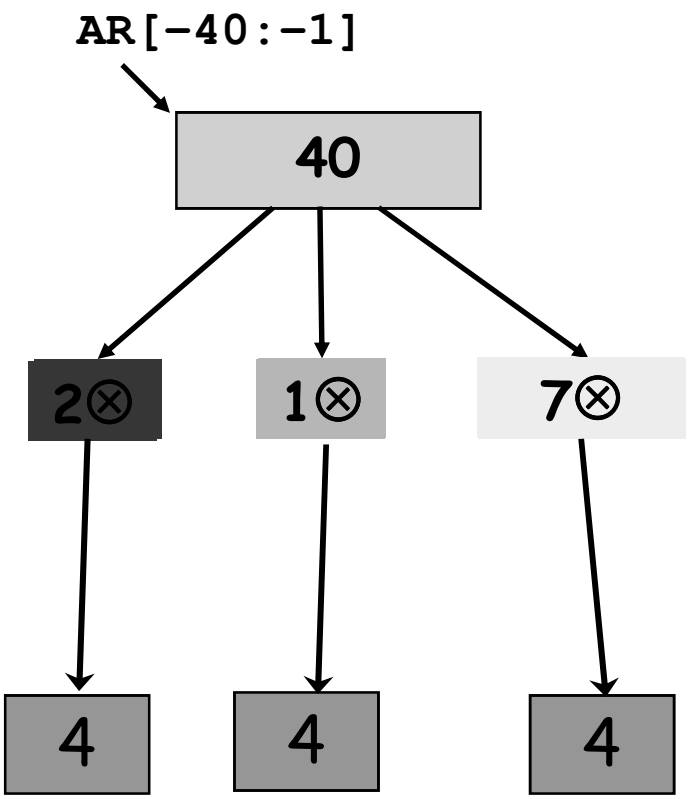

Aggregate Structure Identification

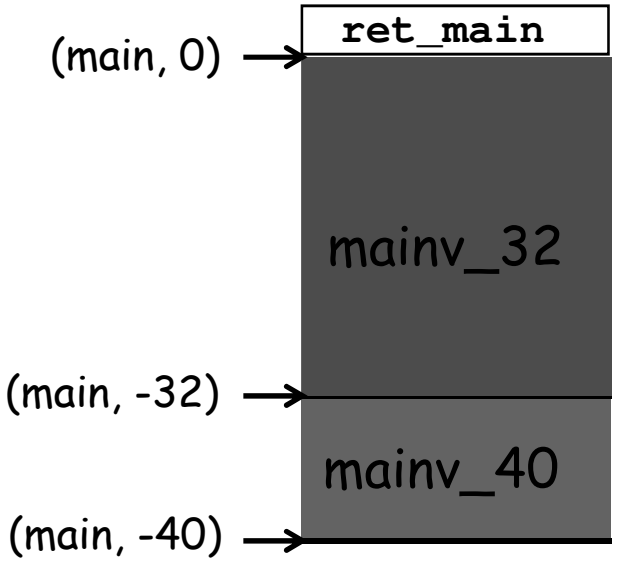


ASI: two arrays; one scalar

```
; ebx ⇔ variable i
; ecx ⇔ variable p

sub     esp, 40         ;adjust stack
lea     edx, [esp+8]    ;
mov     [4], edx        ;pArray2=&a[2]
lea     ecx, [esp]      ;p=&a[0]
mov     edx, [0]        ;

loc_9:
   mov     [ecx], edx   ;*p=arrVal
   add     ecx, 4       ;p++
   inc     ebx          ;i++
   cmp     ebx, 10      ;i<10?
   jl      short loc_9  ;

mov     edi, [4]     ;
mov     eax, [edi]   ;return *pArray2
add     esp, 40
retn
```

Aggregate Structure Identification

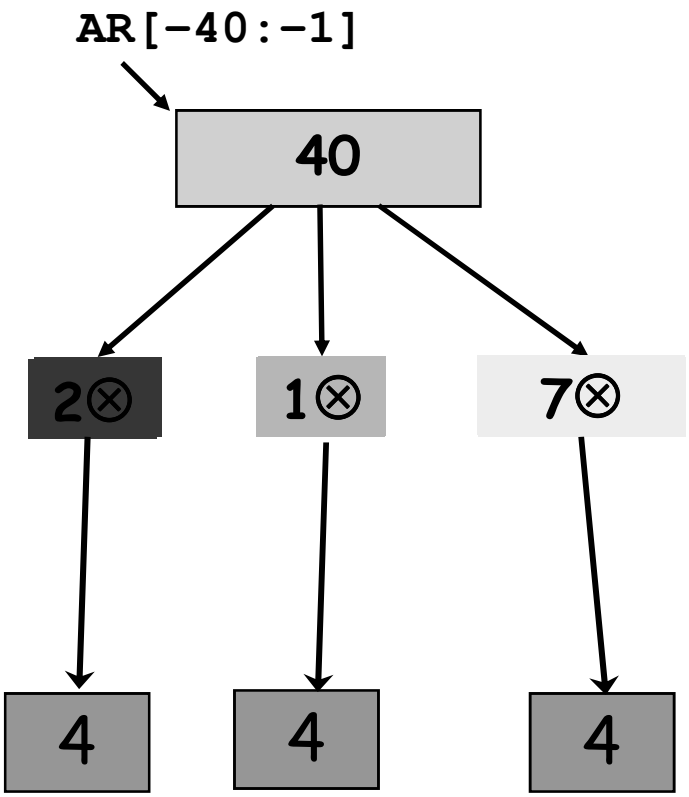




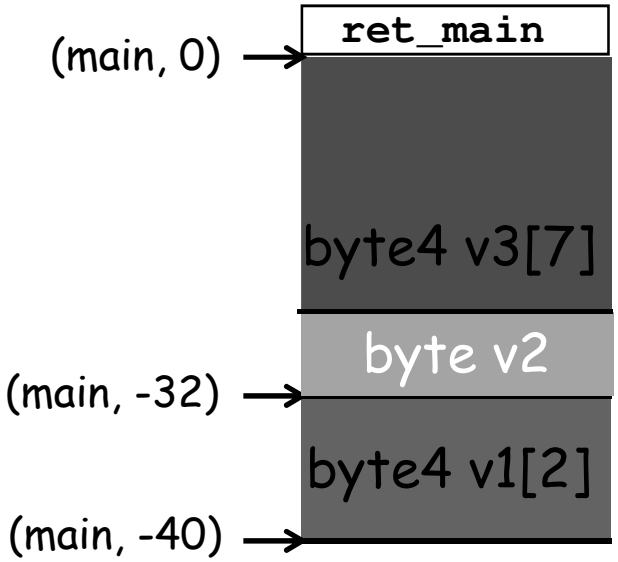
Region for **main**

ASI: two arrays; one scalar

Aggregate Structure Identification



ASI: two arrays; one scalar

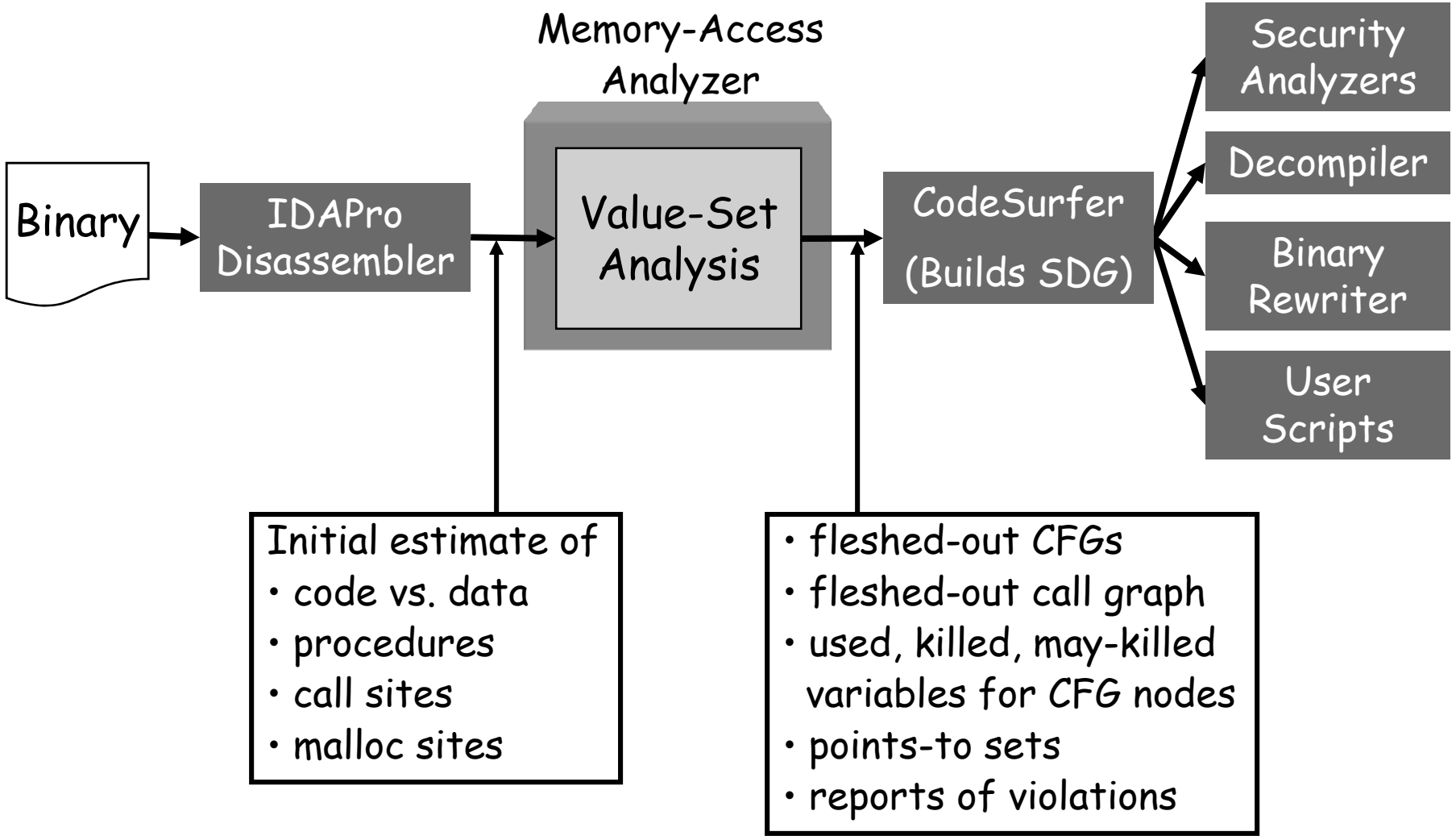


Region for **main**

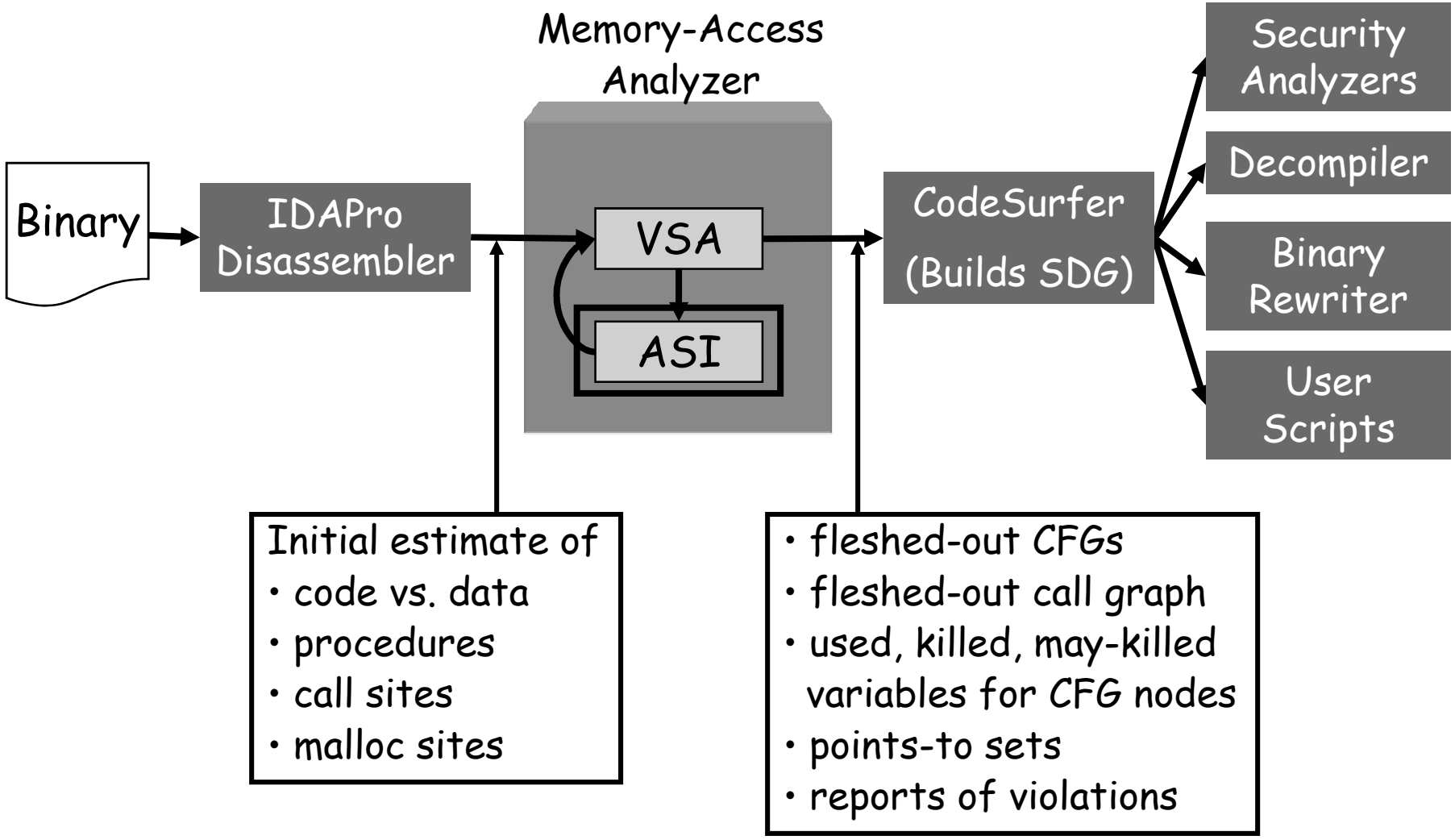
High level type:

```
struct {
   int v1[2];
   int v2;
   int v3[7];
};
```

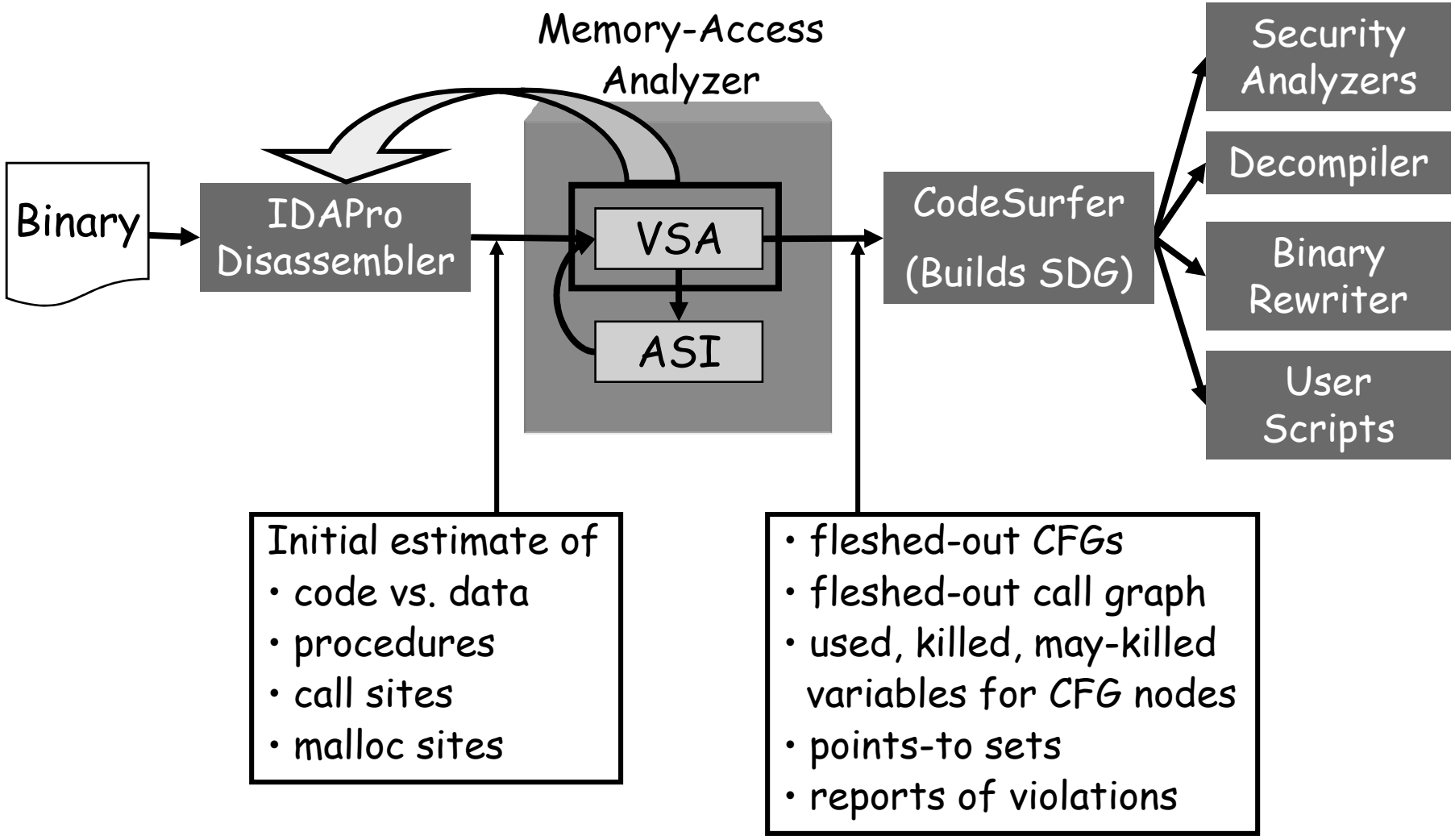
CodeSurfer/x86 Architecture



CodeSurfer/x86 Architecture



CodeSurfer/x86 Architecture



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PDEVICE_OBJECT
LONG
PVOID
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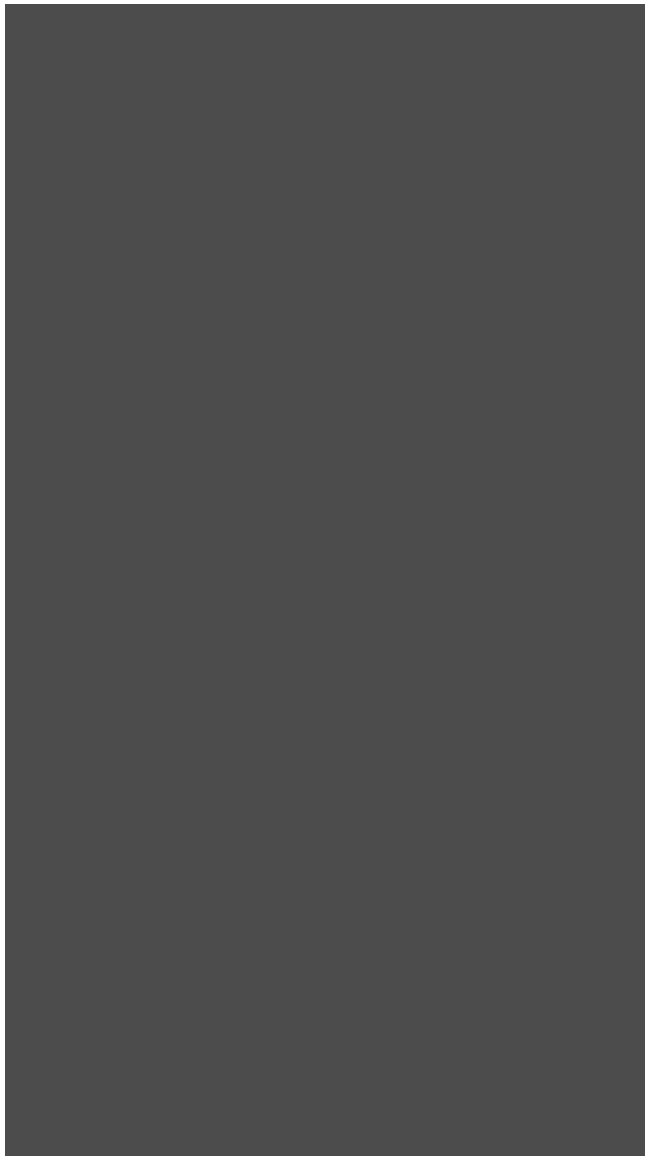
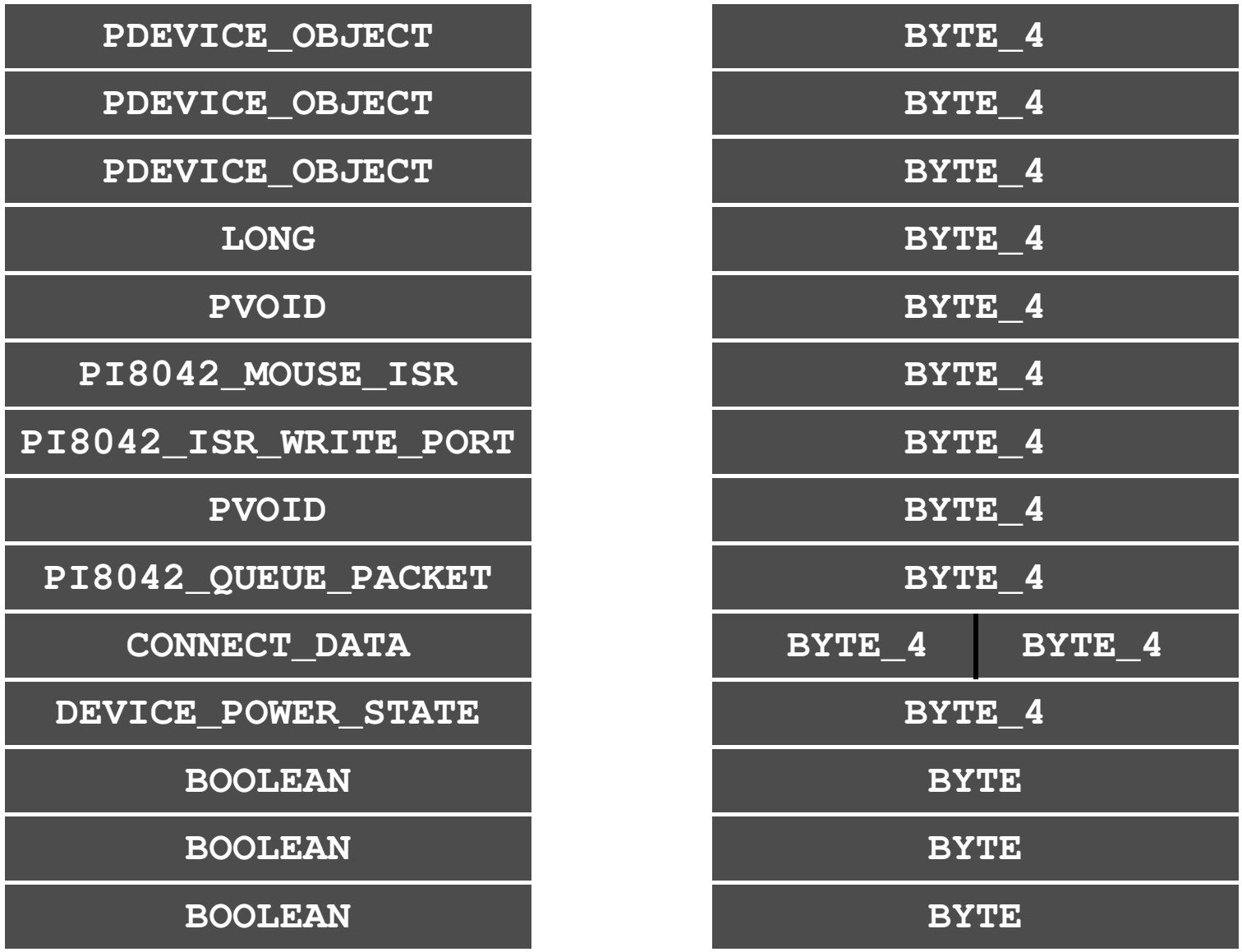
PI8042_ISR_WRITE_PORT
PVOID
PI8042_QUEUE_PACKET
CONNECT_DATA
DEVICE_POWER_STATE
BOOLEAN
BOOLEAN
BOOLEAN

Declaration in C Source



Structure in Executable

Device Extension Structure for "moufiltr" driver



Declaration in C Source

Structure identified by CS/x86

Outline

- CodeSurfer/x86 architecture
- Challenges
- Core Analysis Algorithms
  - Recovering variable-like entities (a-loc)
  - Value-set Analysis (VSA)
  - Other Algorithms
- Device-Driver Analysis
  - Improved a-loc recovery
- What Next?

Other Uses for IR – Early Adopters

- Malicious code analysis - MIT Lincoln Labs
  - Given a worm . . .
    - What are its target-discovery, propagation, and activation mechanisms?
    - What is its payload?

- Extracting file formats from executables
  - J. Lim, T. Reps, B. Liblit (UW) [WCRE06]
  - Based on the file operations in the executable
    - Extract the format of the file being read or written to

- Extracting summaries for library functions
  - D. Gopan and T. Reps (UW) [CAV07]
  - Use information from VSA to extract numeric programs
  - Analyze numeric programs to generate summaries (for memory-safety properties)

What Next?

- Adapt to source code
  - High fidelity information in executables
    - e.g., Buffer Overflow
      - can pin-point the out-of-bounds variable that is touched
  - Useful in source-code analysis
    - e.g., to generate/find non-control data attacks

- Combine dynamic and static techniques
  - Polymorphic viruses and worms
  - Self-modifying code
  - etc.,

What Next?

- Automate Abstraction-Refinement
  - Required a lot of manual effort
    - to reduce false positives in device-driver analysis
  - Automate the process of refinement
    - Lazy Abstraction [Henzinger et al. POPL02]
    - Property simulation [Das et al. PLDI02, SAS06]
  - Seems to be the way to go...

- Lots of other applications
  - Binary-compatibility checking
  - Classifying malware
  - etc.

Summary

- The Vision: A platform for analyzing executables
  - Recover IR from stripped executables
  - Use IR for further analysis

- Why Executables?
  - Source code may not be available
  - Allows analysis of library code
  - Better for security analysis

- How can we build the tool?
  - Value-set analysis (VSA) [CC04]
    - A combined pointer-analysis and numeric-analysis algorithm
  - Algorithm to recover variable-like entities in executables [VMCAI07]
  - Recency-abstraction for heap-allocated data [SAS06]
  - Other analysis
    - ARA, low-level ESP, etc.

G. Balakrishnan and T. Reps, "Analyzing memory accesses in x86 executables," CC 2004, www.cs.wisc.edu/~reps/#cc04

T. Reps, G. Balakrishnan, J. Lim, and T. Teitelbaum, "A next-generation platform for analyzing executables," APLAS 2005, www.cs.wisc.edu/~reps/#aplas05.invited

T. Reps, G. Balakrishnan, and J. Lim, "Intermediate-representation recovery from low-level code," PEPM 2006, www.cs.wisc.edu/~reps/#pepm06.invited

G. Balakrishnan and T. Reps, "Recency-abstraction for heap-allocated storage", SAS 2006, www.cs.wisc.edu/~reps/#sas06-recency

G. Balakrishnan and T. Reps, "DIVINE: DIscovering Variables IN Executables," VMCAI 2007, www.cs.wisc.edu/~reps/#vmcai07.invited

G. Balakrishnan and T.Reps, "Analyzing Stripped Device-Driver Executables," TACAS 2008

WYSINWYX: What You See Is Not What You eXecute
(Static Analysis of Executables)

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Work done while at UW Madison with J.Lim (UW), T. Reps (UW, GrammaTech), T. Teitelbaum (Cornell, GrammaTech)