PtrSplit: Supporting General Pointers in Automatic Program Partitioning

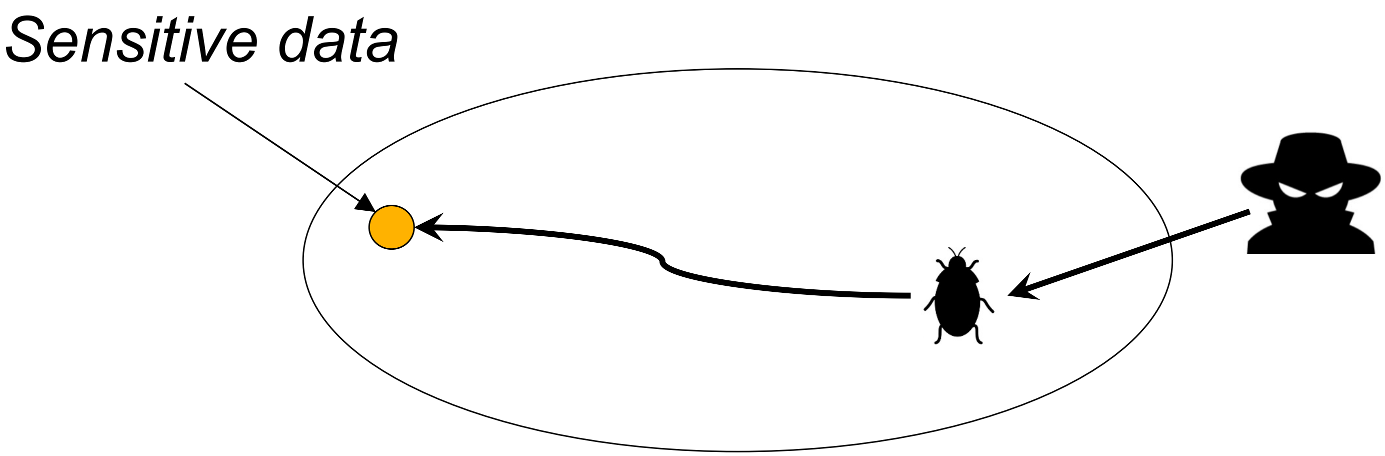
Shen Liu Gang Tan Trent Jaeger

Computer Science and Engineering Department

The Pennsylvania State University

11/02/2017

Motivation for Partitioning

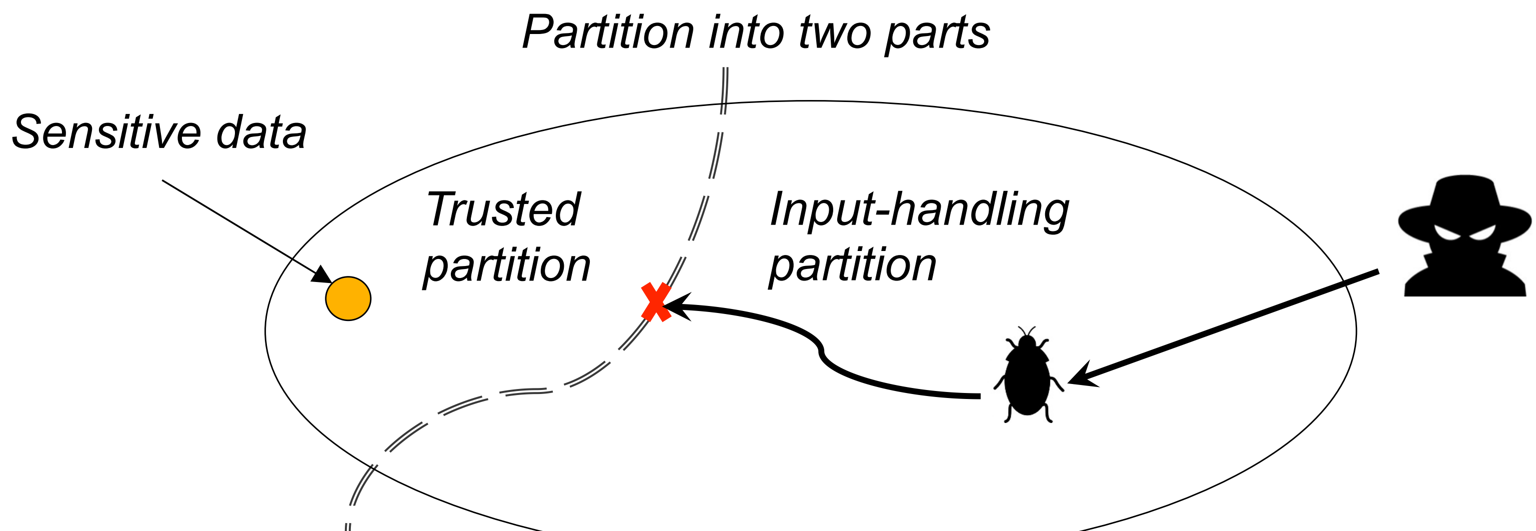


A monolithic, security-sensitive program

A single bug would defeat the security of the whole application

Motivation for Partitioning

- Split the application into multiple partitions
- Each partition is isolated using some isolation mechanism such as OS processes



Although some partition of a program has been hijacked,sensitive data can still be protected

Toy Example

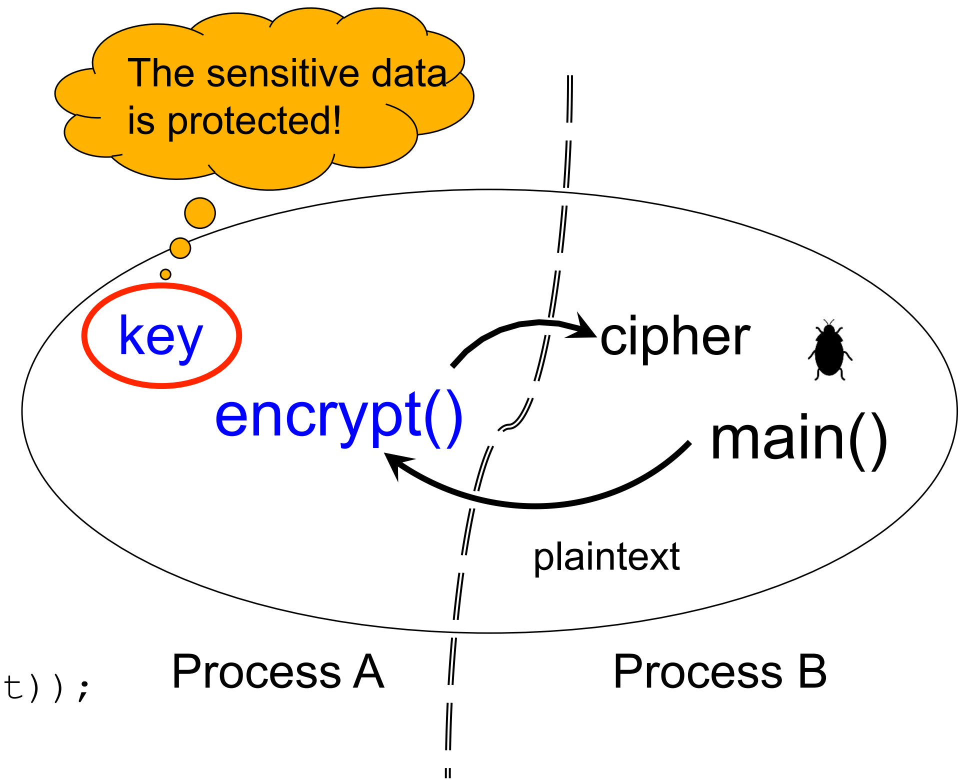
```c
char* cipher;
char* key;

void encrypt(char *plain, int n){
  cipher =(char*)malloc(n);
  for (i = 0; i < n; i++)
    cipher[i] = plain[i] ^ key[i];
}

void main (){
  char plaintext[1024];
  scanf("%s",plaintext);
  encrypt(plaintext,strlen(plaintext));
  ...
}
```

Sensitive data

Buffer overflow

Toy Example

```
char* cipher;
char* key;

void encrypt(char *plain, int n){
  cipher =(char*)malloc(n);
  for (i = 0; i < n; i++)
    cipher[i] = plain[i] ^ key[i];
}

void main (){
  char plaintext[1024];
  scanf("%s",plaintext);
  encrypt(plaintext,strlen(plaintext));
  ...
}
```



Solution

- Manual partitioning
  - do **code review** and extract the sensitive components
  - The amount of code for analysis may be huge…

- Automatic partitioning
  - Given some security criterions, do partitioning based on **static program analysis**
  - Reduce manual effort and errors

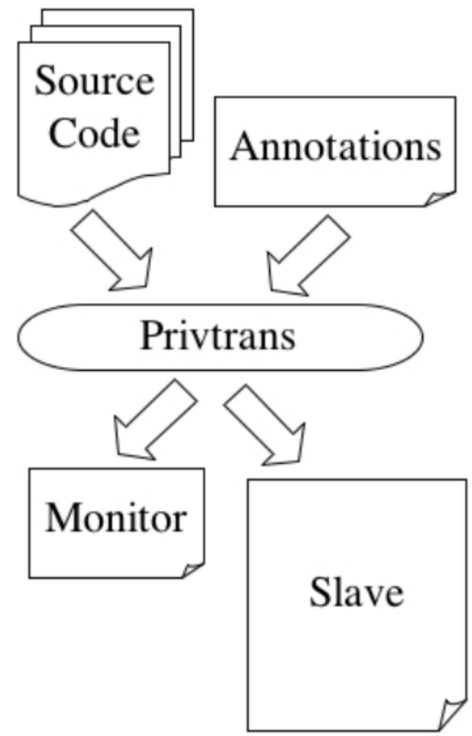
Background: static program analysis

- Static analysis
  - Analyzing code without executing it
  - Static analysis can be considered as automated code review
  - e.g. Annotate a sensitive variable key, we can find all the statements that key can reach to.

```
char* cipher;
char* key;

void encrypt(char *plain, int n){
  cipher =(char*)malloc(n);
  for (i = 0; i < n; i++)
    cipher[i] = plain[i] ^ key[i];
}

void main (){
  char plaintext[1024];
  scanf("%s",plaintext);
  encrypt(plaintext,strlen(plaintext));
  ...
}
```

Previous Work: Privtrans(2004)

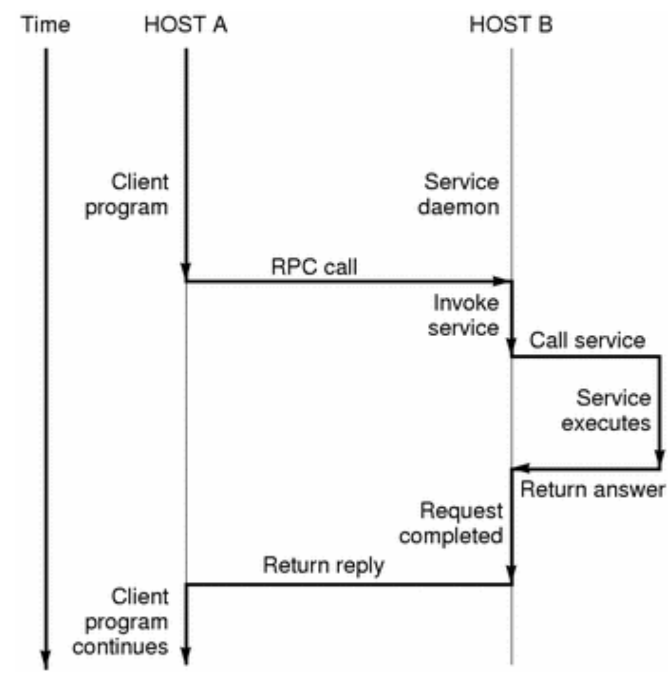
- Privtrans automatically incorporate privilege separation into source code by partitioning it into two programs
  - A **monitor** program which handles privileged operations
  - A **slave** program which executes everything else
  - Users need to manually add a few annotations to help Privtrans decide how to partition
  - The inter-process communication between monitor and slave is implemented by Remote Procedure Call(RPC)



Privtrans' principle (copied from the paper)

Background: Remote Procedure Call(RPC)

- RPC allows a program to call procedures that run in a different address space
  - Programmers need to tell RPC what functions will be called remotely, and define the interfaces(IDL file)
  - RPC can generate code to transmit data between the client and servers
  - Data transmission is done through the network



How RPC works(copied from the TI-RPC manual)

Previous Work

- Systems for automatic program partitioning
  - **Privman** by Kilpatrick (USENIX ATC 2003)
  - **Ptrivtrans** by Brumley and Song (USENIX Security 2004)
  - **Wedge** by Bittau, Marchenko, Handley, and Karp (USENIX NSDI 2008)
  - **ProgramCutter** by Wu, Sun, Liu, and Dong (ASE 2013)

- One major limitation: lack automatic support for pointers
  - Pointers prevalent in C/C++ applications
  - Previous work
    - Lack sound reasoning of pointers for partitioning
    - Require manual intervention when pointers are passed across partition boundaries

Background: Aliases

- What will happen when two pointers refer to the same memory location

```
Example 1:
int x;
p = &x;
q = p; // <*p,*q>,<x,*p> and <x,*q> are all aliases now

Example 2:
int i,j, a[100];
i = j; // a[i] and a[j] are aliases now
```

- Alias analysis is undecidable(G. Ramalingam, TOPLAS 1994)
  - –For large programs, alias analysis will be a disaster(e.g. linux kernel)

Difficulty in Supporting Pointers in Automatic Program Partitioning

- Claim: For sound program partitioning, has to reason about program dependence with aliasing
  - Need global pointer analysis for tracking dependence on programs with pointers
  - Global pointer analysis is complex and unscalable

- What happens when pointers are passed across boundaries?
  - Passing pointers alone insufficient when caller and callee are in two different address spaces
  - We use deep copying: passing pointers as well as their underlying buffers
    - However, C-style pointers do not carry bounds information
    - Do not know the sizes of the underlying buffers

Our Work: PtrSplit

- PtrSplit provides automatic support for program partitioning with pointers
  - Perform program partitioning based on Program Dependence Graphs (PDG), which track program dependences
- **Parameter-tree**-based PDG
  - Avoid global pointer analysis
  - Modular construction of the dependence graph
- Automated marshalling/unmarshalling for cross-boundary data, even with pointers
  - **Selective pointer bounds tracking**: track bounds only for necessary pointers
    - Avoid high overhead
  - **Type-based marshaling/unmarshalling**: use bounds information to perform deep copying

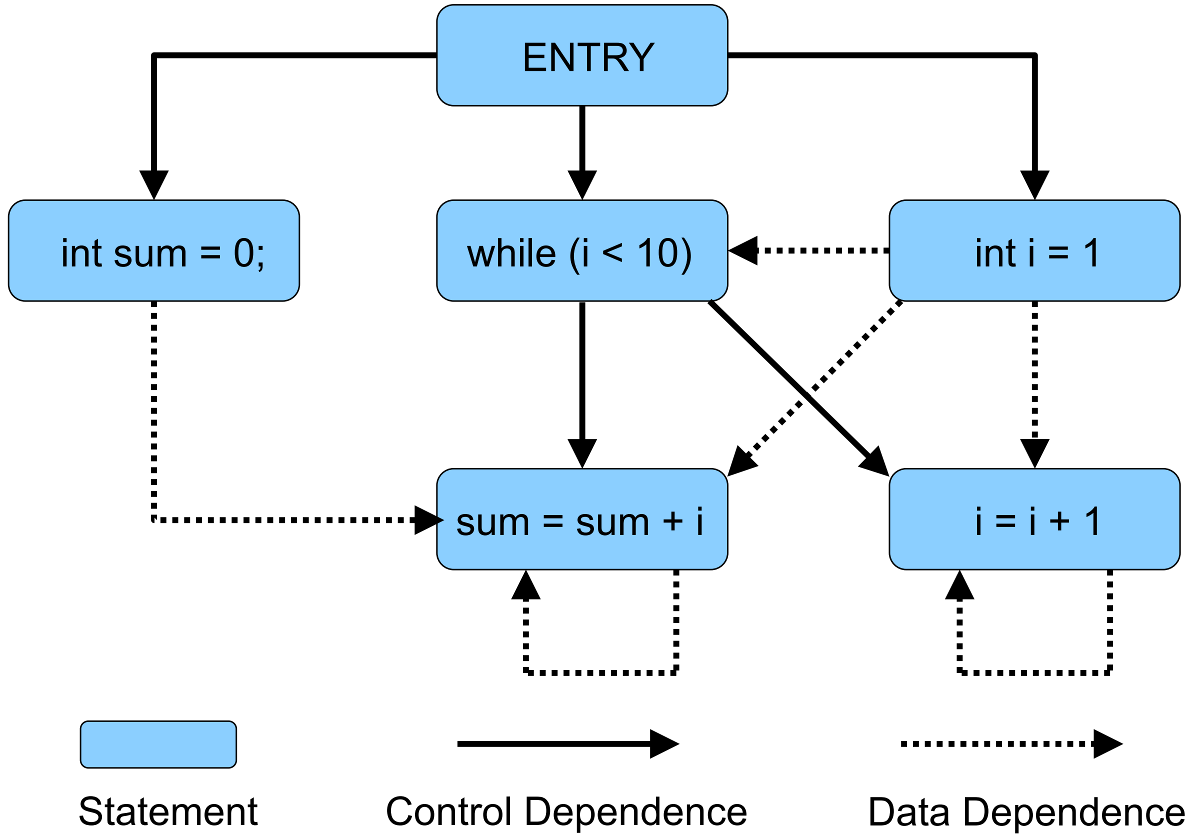
Background: Program Dependence Graph(PDG)

- PDG is a **graphical representation** of the program
  - Program statements are represented as “nodes”
  - The dependencies among different statements are represented as “edges”

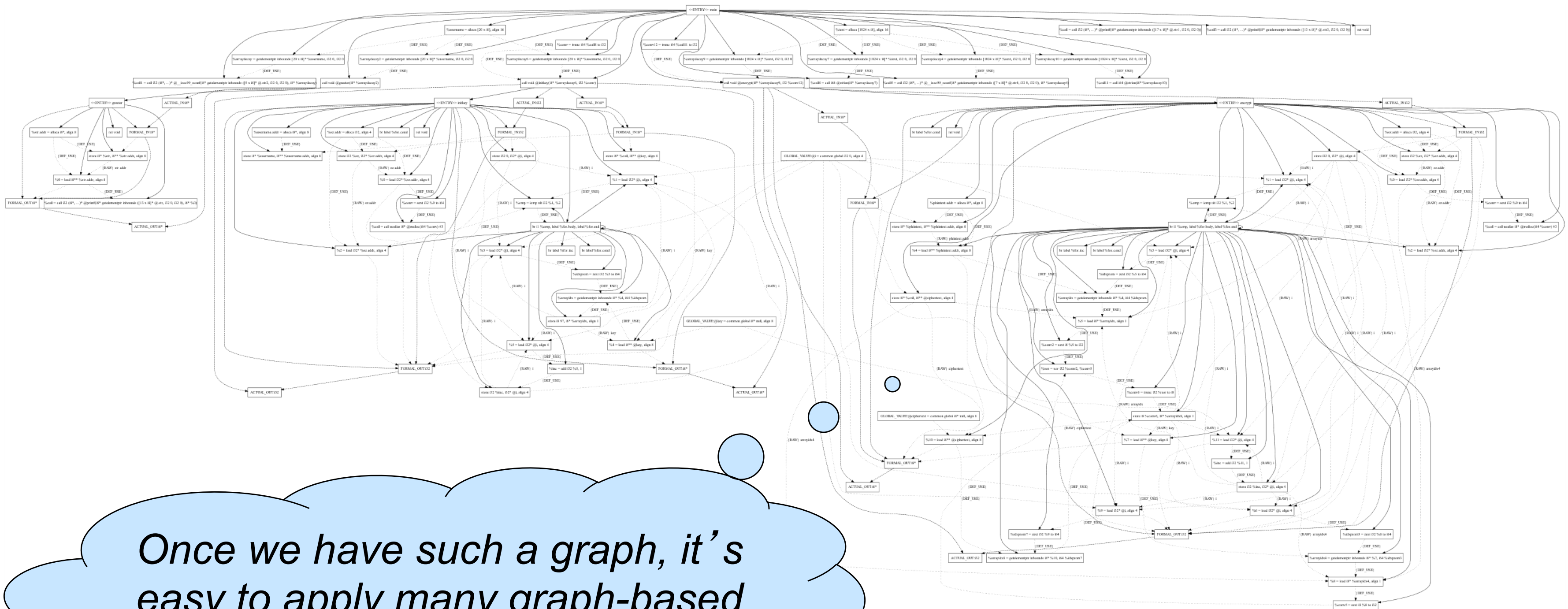
- In a PDG there exist two kinds of dependence
  - **Control dependence** describes the control relationships caused by conditional statements(if-else/switch) and circular statements (for/while loops)
  - **Data dependence** describes the relationship caused by assignment statements

Program Dependence Graph: Example

```
void sum{
    int sum = 0;
    int i = 1;
    while ( i < 10 ){
        sum = sum + i;
        i = i + 1;
    }
}
```

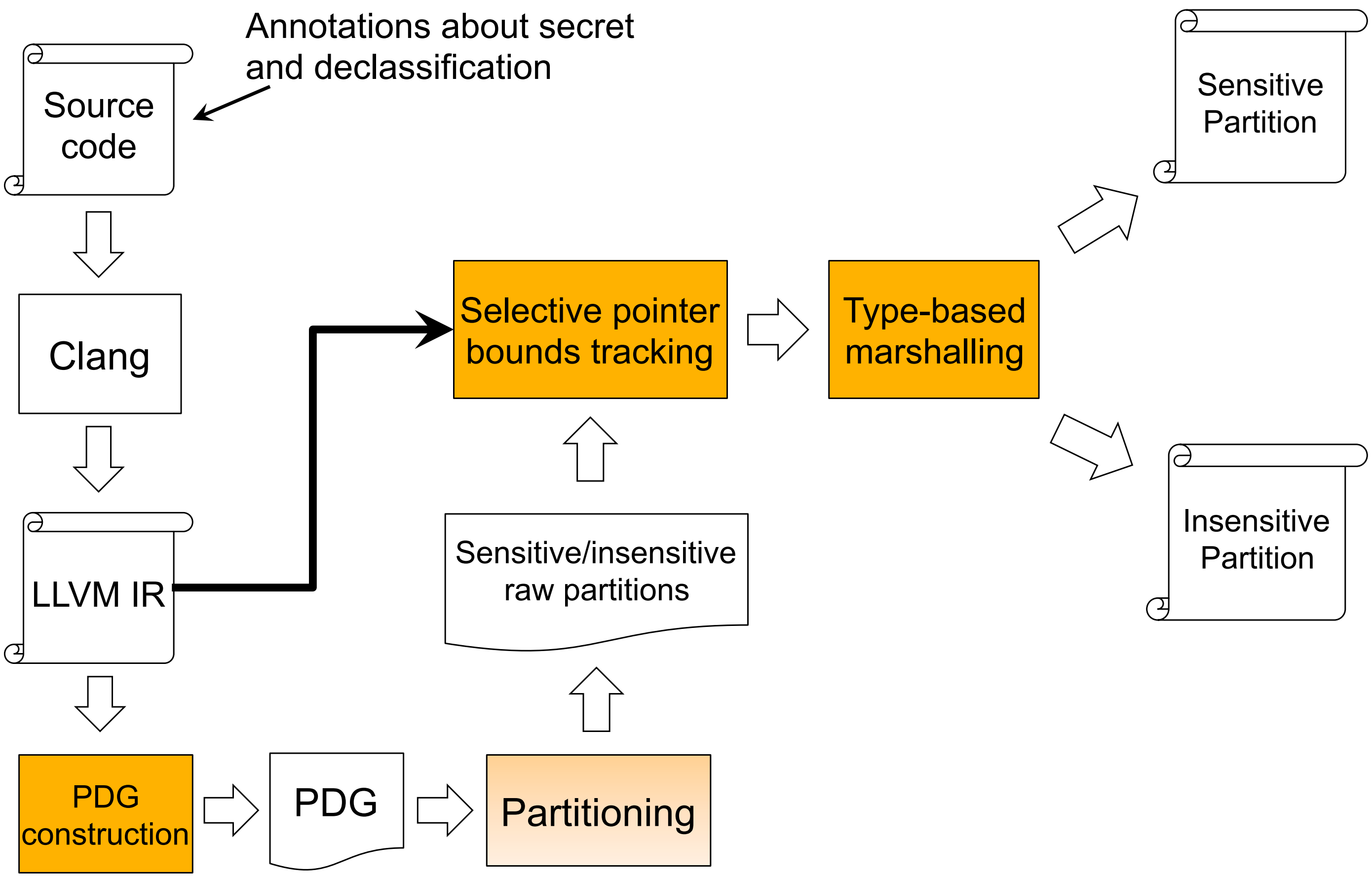


A Parameter-tree-based PDG



Once we have such a graph, it's easy to apply many graph-based algorithms…

Basic Workflow



Program Dependence Graph (PDG) Construction

- We build a **parameter-tree**-based PDG
  - Represent a program's data and control dependence in a single graph
  - Sound representation of a program's control/data dependence
  - Modular construction through parameter trees

Motivation of Parameter Trees

- Pointers make building dependence graphs hard
- Inter-procedural dependences require global pointer analysis
- However, global pointer analysis is complex and unscalable

```
char* cipher;
char* key;

void encrypt(char *plain, int n){
  cipher =(char*)malloc(n);
  for (i = 0; i < n; i++)
    cipher[i] = plain[i] ^ key[i];
}

void main (){
  char plaintext[1024];
  scanf("%s",plaintext);
  encrypt(plaintext,strlen(plaintext));
  ...
}
```

Memory Read

Read-after-write dependence

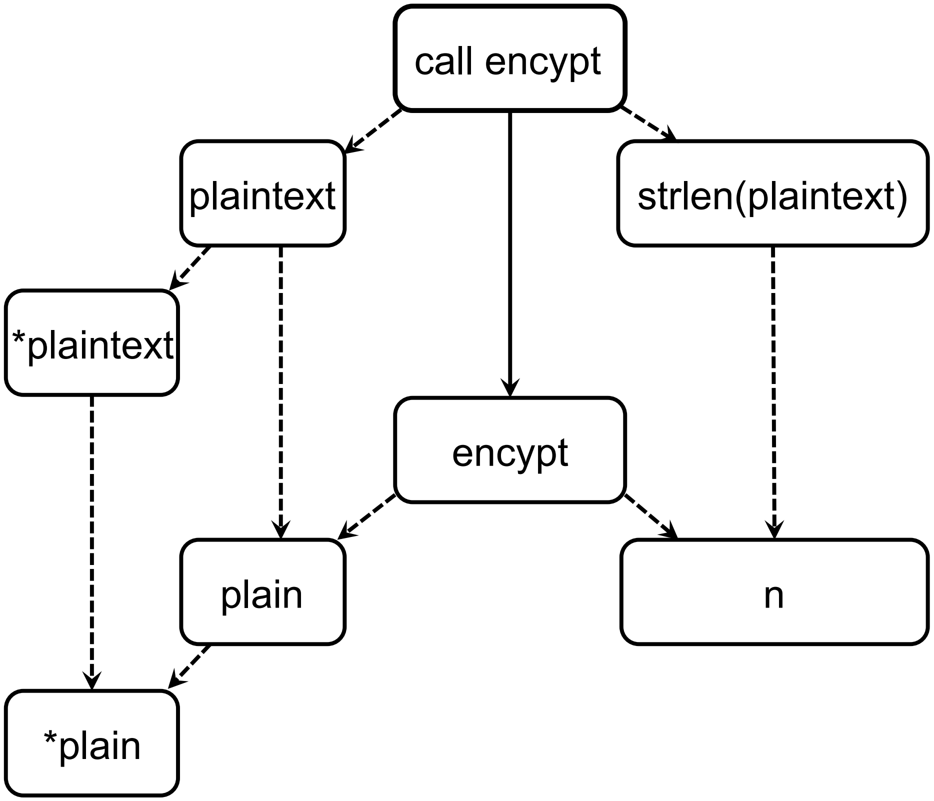
Memory Write

Parameter Trees

- Goal: make the PDG construction efficient and sound
  - For each parameter of a function, we build a formal parameter tree according to the parameter's type
  - Similarly, at a call site of a function, we build a parameter tree for every argument
  - A caller and its callee can be connected by connecting the corresponding nodes in the actual and formal parameter trees
- Our tree representation generalizes the object-tree approach and deals with circular data structures resulting from pointers
  - Slicing Objects Using System Dependence Graphs. D. Liang and M.J. Harrold (ICSM 1998)
  - Prior work did not cover pointers at the language level

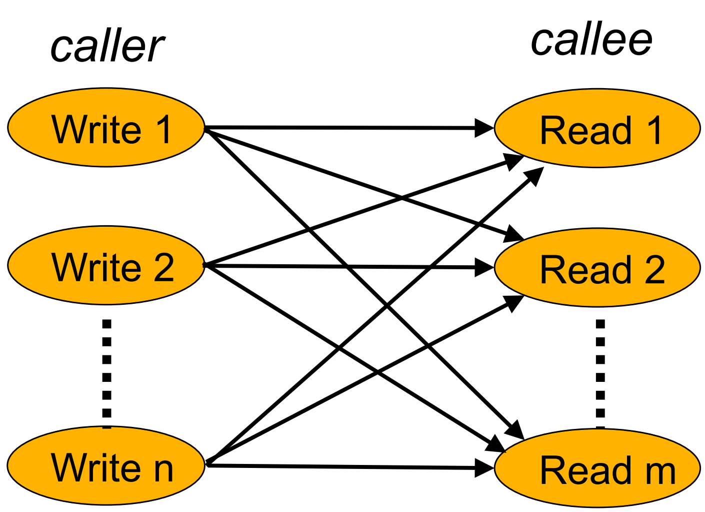
Parameter Tree: Example

```
char* cipher;
char* key;

void encrypt(char *plain, int n){
  cipher =(char*)malloc(n);
  for (i = 0; i < n; i++)
    cipher[i] = plain[i] ^ key[i];
}

void main (){
  char plaintext[1024];
  scanf("%s",plaintext);
  encrypt(plaintext,strlen(plaintext));
  ...
}
```

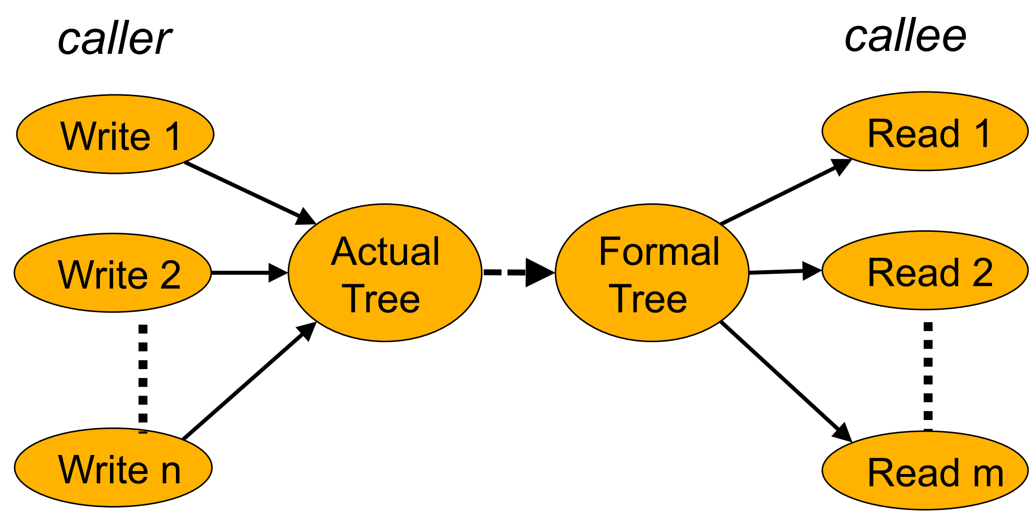


Benefits of Parameter Trees

- Avoid global pointer analysis
  – only intra-procedural pointers analysis is needed
- Reduce the number of dependence edges: suppose n writes and m reads



No parameter trees: *O(n*m) edges*



With parameter tree: *O(n+m) edges*

PDG-based Partitioning

- After the PDG construction, we perform PDG-based partitioning
- Input: sensitive and declassification nodes
- Output: two partitions
  – each partition is a set of functions and global variables
- Potential problem: only raw partitions can be generated
  – Inter-module communication overhead may be huge…
  – e.g. If we partition a program with 1000 functions into two, we may get a partition with 600 functions and another partition with 400 functions

Use declassification to adjust the partitioning boundary

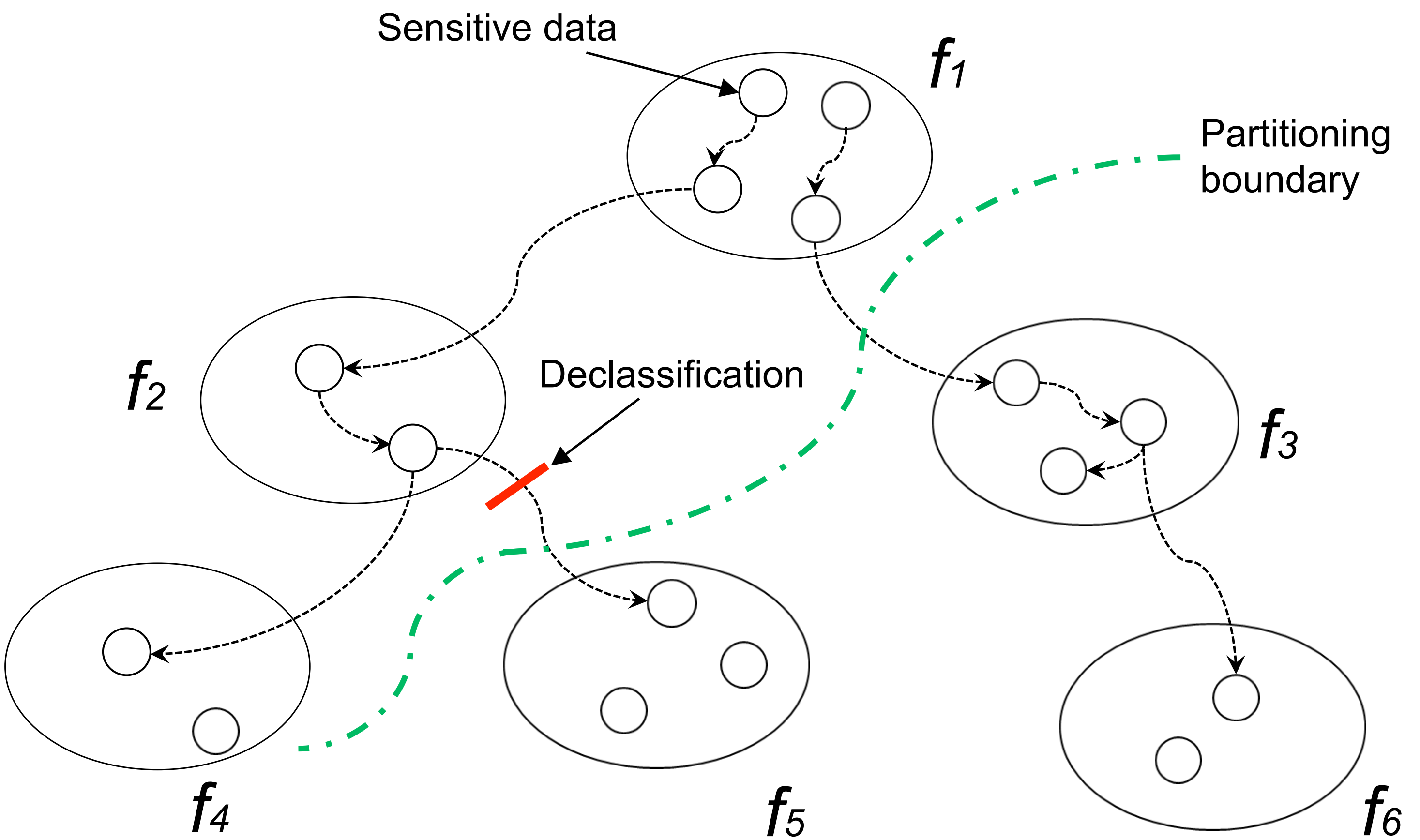
- PDG-based partitioning may give us a very awkward result
  – e.g. a sort function inside a 3-level loop is called remotely
- To balance the security and performance, we use declassification to prevent some sensitive dataflows
- Example:

1 byte only

```
bool authenticate(char* s1, char* s2){…}
…
for(…){
       if(authenticate(password,input) == true){…}
}
```

(We can declassify authenticate's return value since there isn't too much sensitive information leakage here – should limit number of calls to authenticate)

PDG-based Partitioning: Example



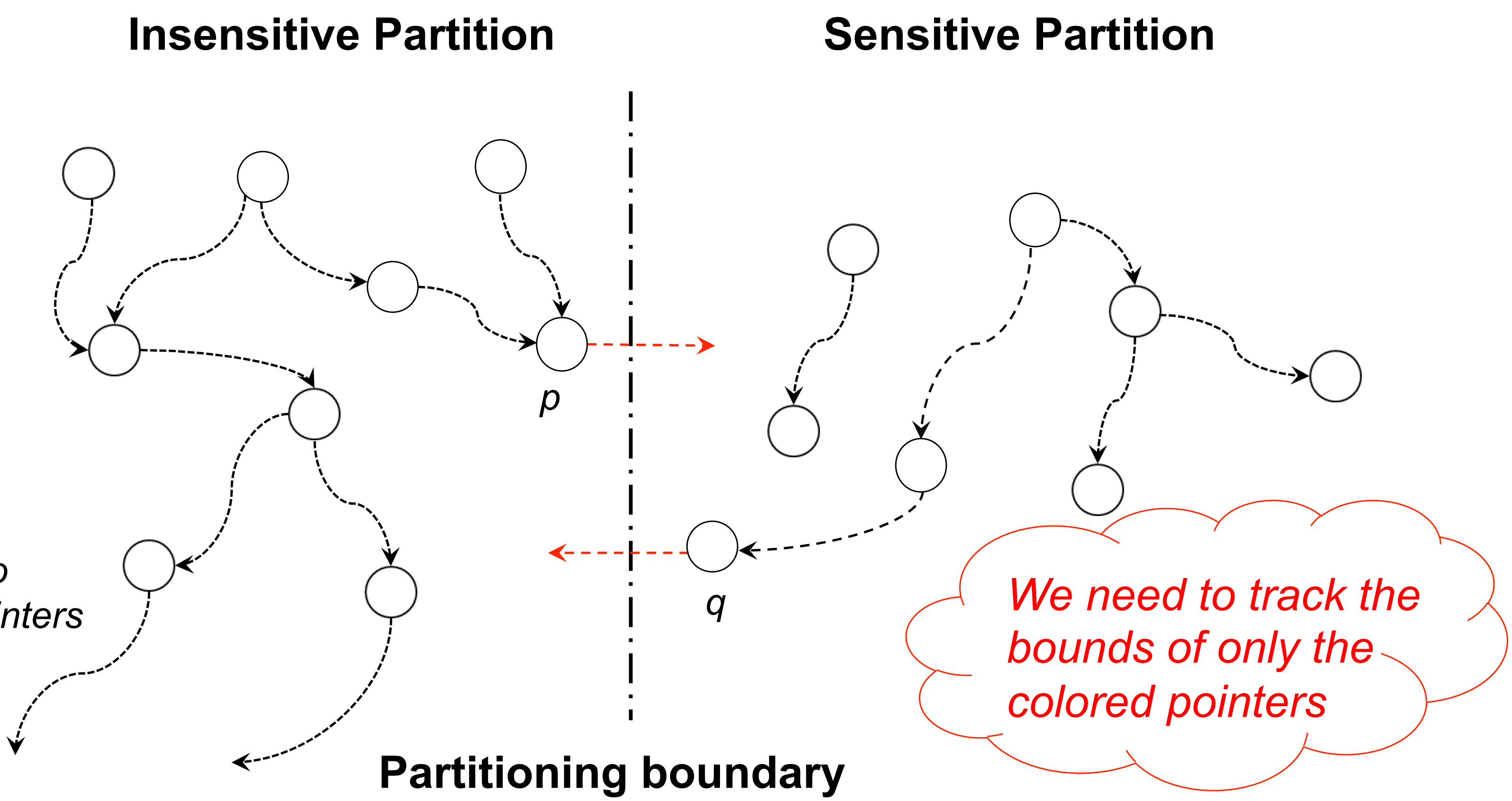
Selective Pointer Bounds Tracking

- Why we need to know the buffer size?
  - When pointers are passed across the partition boundary, we deep copy pointers and their underlying buffers
- How to calculate the buffer size?
  - Use bounds tracking tools
- Several tools for enforcing memory safety track bounds at runtime
- However, enforcing memory safety incurs high performance overhead
  - E.g. SoftBound’s performance overhead on the SPEC and Olden benchmarks is 67% on average
- Improvement
  - For marshalling and unmarshalling it is necessary to perform only **bounds tracking, but not bounds checking**
  - We care about only the bounds of pointers that can **cross the boundary** of partitions

Selective Pointer Bounds Tracking

Step 1
Find pointers that are sent across the boundary

Step 2
Do backward propagation to find all BR pointers



Automatic Support of Marshalling and Unmarshalling

- Since partitions are loaded into separate processes, some function calls are turned into Remote Procedure Calls (RPCs)
  – Straightforward for values of most data types, including integers, arrays of fixed sizes, and structs
  – For pointers, the underlying buffer sizes can be tracked with SPBT

- When a pointer is passed across the boundary, we perform deep copying
  – After marshalling, arguments of a function call are encoded as a byte array, which is sent to the receiver via the help of an RPC library

Experiments

- We implemented PtrSplit on LLVM 3.5, which supports both DSA alias analysis and SoftBound
  - SoftBound keeps the bound information as metadata for each pointer
  - All bounds checking operations removed
  - Only BR-pointers are instrumented
  - RPC library: TI-RPC
- Robustness testing
  - 8 benchmarks from SPECCPU2006
- Security testing
  - 4 security-sensitive programs

Example: thttpd

- Sensitive data: authentication file
- Declassification: the return result (integer) of function auth_check
- Full pointer bounds tracking overhead : 56.3%
  – Selective pointer bounds tracking overhead: 3.6%
- A total of 5 out of 145 functions are marked sensitive
  – Total overhead: 8.8%

Result: Security-sensitive Programs

Program	Sensitive Data	Declassifications	Total Functions	Sensitive Functions
ssh	Private key file	2	1235	12
wget	Downloaded file	2	666	8
thttpd	Authentication file	1	145	5
telnet	Received data from server	3	180	11

Program	Total/BR pointers	Full PBT overhead	Selective PBT overhead	Total overhead
ssh	21020/591	45.0%	2.6%	7.4%
wget	14939/466	52.5%	3.4%	6.5%
thttpd	3068/189	56.3%	3.6%	8.8%
telnet	2068/233	74.1%	5.1%	9.6%

Selective bounds tacking greatly reduced overhead

Experiments: SPECCPU 2006 programs

- Not suitable for security experiments, only used for correctness testing
- Use randomly chosen data as the partitioning start
- Average full pointer bounds tracking overhead : 136.2%
  – Average selective pointer bounds tracking overhead: 7.2%
- Average total overhead: 33.8%

Future Work

- Multi-threading support

- More efficient bounds-tracking
  – LowFat Pointer (NDSS 2017).
  – Checked C (still in development)

- Automatic inference of sensitive data and declassifications
  – Automating Security Mediation Placement (ESOP 2010).

Q&A

Thank you!