Ensuring System Security Using Data Flow Analysis

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Agenda

- Overview of projects
- Dynamic Data Flow Analysis (DDFA) details
- Process Coloring (PC) details
- DDFA+PC demonstration

Project Overview

- Researching software and system security for Intelligence Advanced Research Projects Activity (IARPA)
- Two separately funded projects
  - Dynamic Data Flow Analysis for Improving Software Security
    - SwRI and UT Austin
  - Process Coloring: An Information Flow-Preserving Approach to Malware Investigation
    - Purdue
- Projects started June 2007
- Projects scheduled to finish December 2008

Project Collaborators

- Dynamic Data Flow Analysis (DDFA):

Jeremy Price, Mark Brooks, Steve Cook, Arif Kasim
Southwest Research Institute
Calvin Lin, Walter Chang
Department of Computer Science
University of Texas at Austin

- Process Coloring:

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Department of Computer Science and
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Purdue University
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Project Roles

- UT Austin
  - Research and implementation of DDFA core
    - pointer analysis, policy language, compiler infrastructure
- SwRI
  - Technology transfer
  - Hardening of DDFA core
  - Collaboration and integration efforts
- Purdue
  - Research and implementation of PC core
    - Xen changes, Linux kernel changes, flow infrastructure

The Problem

- Create secure computing environments from commodity software
- Most commodity software not designed with security in mind

What Does "Secure" Mean?

- Some answers are easy to define
- Example: We want our programs to exhibit memory safety
  - Memory safety: It's only possible to read and write memory as intended by the programmer
  - Thus, no buffer overflows, no dangling pointers, no overwriting of the stack
- Other answers are domain-specific
  - SQL-injection
  - Cross-site scripting
  - Information leakage . . .

"Secure" is Also Context-Specific

- Whom do you trust?
- What is the threat model?
- What is your environment?
- Many other possible assumptions

- We can't expect commodity software to be secure

Do We Need Commodity Software?

- Custom software has two costs
  - Fixed cost of writing the software
  - Recurring cost of maintaining and evolving software to keep up with the latest tools, libraries, and standards

Dynamic Data Flow Analysis

UNIVERSITY OF TEXAS AT AUSTIN

What are we trying to do?

- Our approach uses a complementary combination of static and dynamic data flow analysis to enhance programs to enforce a specified security policy
- Utilize trusted compiler technologies to apply user defined security policy
- Automate the application of security to existing C source code
  - Separation of concerns

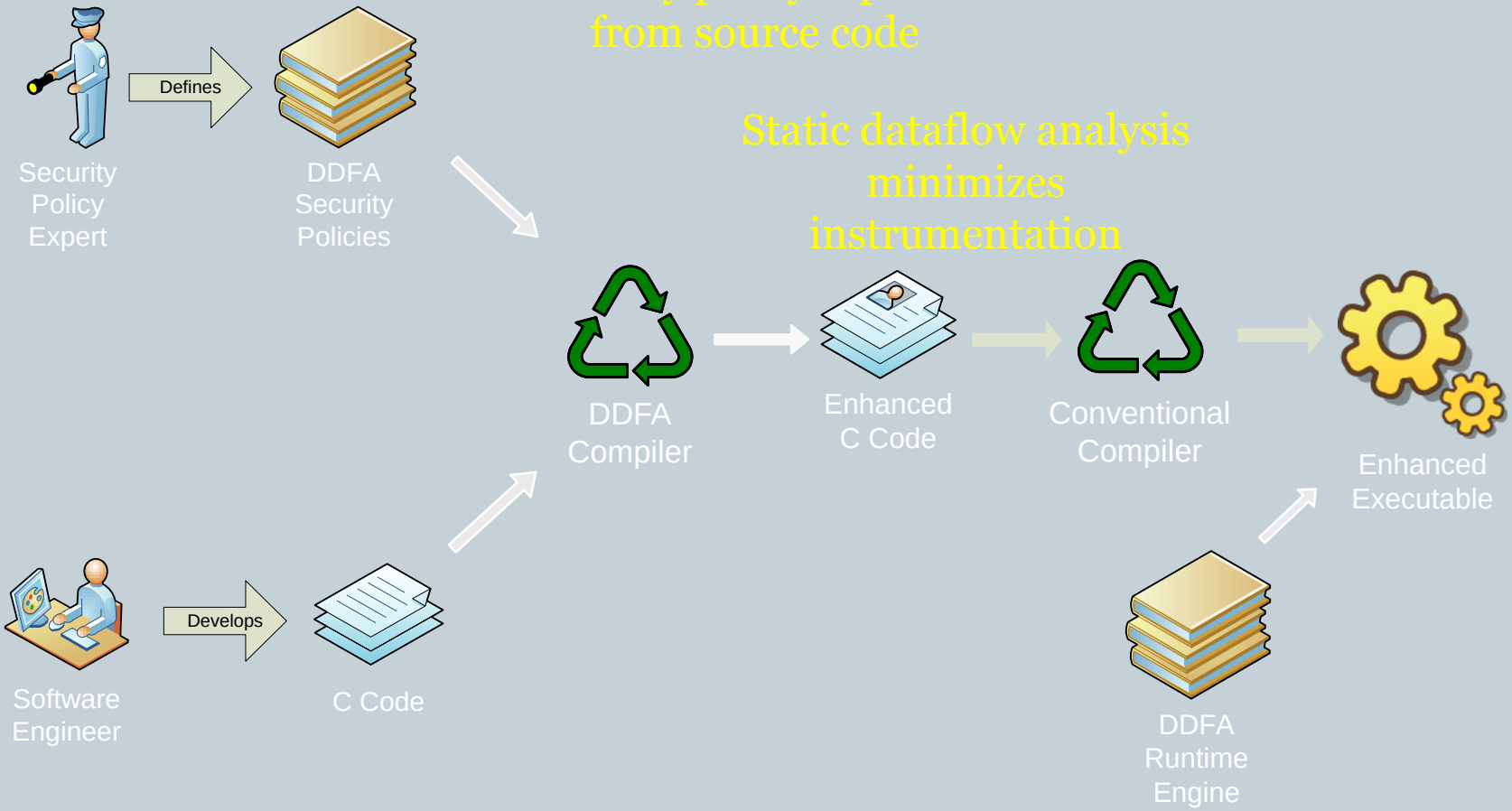
Research Goals

- Minimize the impact to software development
- Keep program runtime and size overhead as low as possible
- Support multi-level security and other complex scenarios
- Extensibility for future threats

Our Approach With DDFA

Security policy separate from source code

Static dataflow analysis minimizes instrumentation

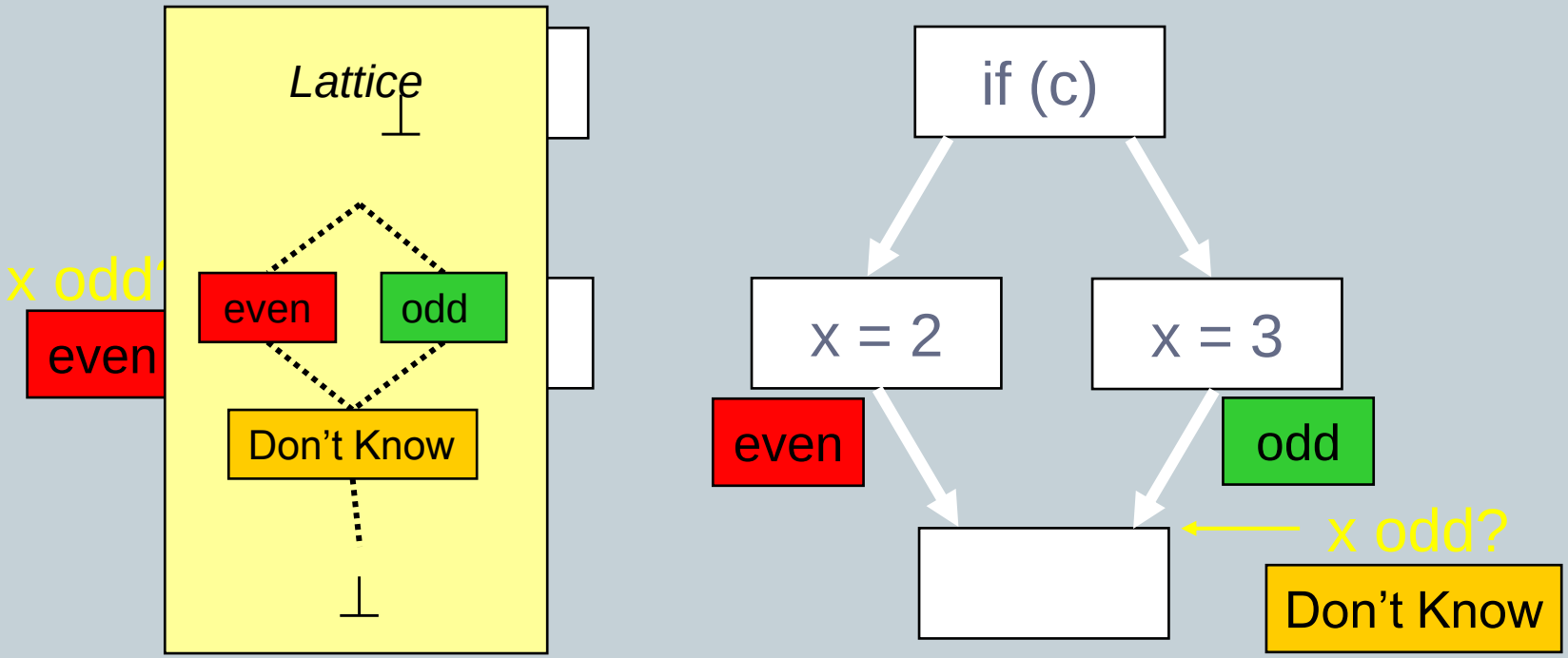


What is Data Flow Analysis?

- One type of static analysis
- Derives information about the dynamic behavior of a program by statically examining the code
- At the heart of many compiler transformations

Data Flow Analysis Example

- Does variable x contain an odd or an even value?

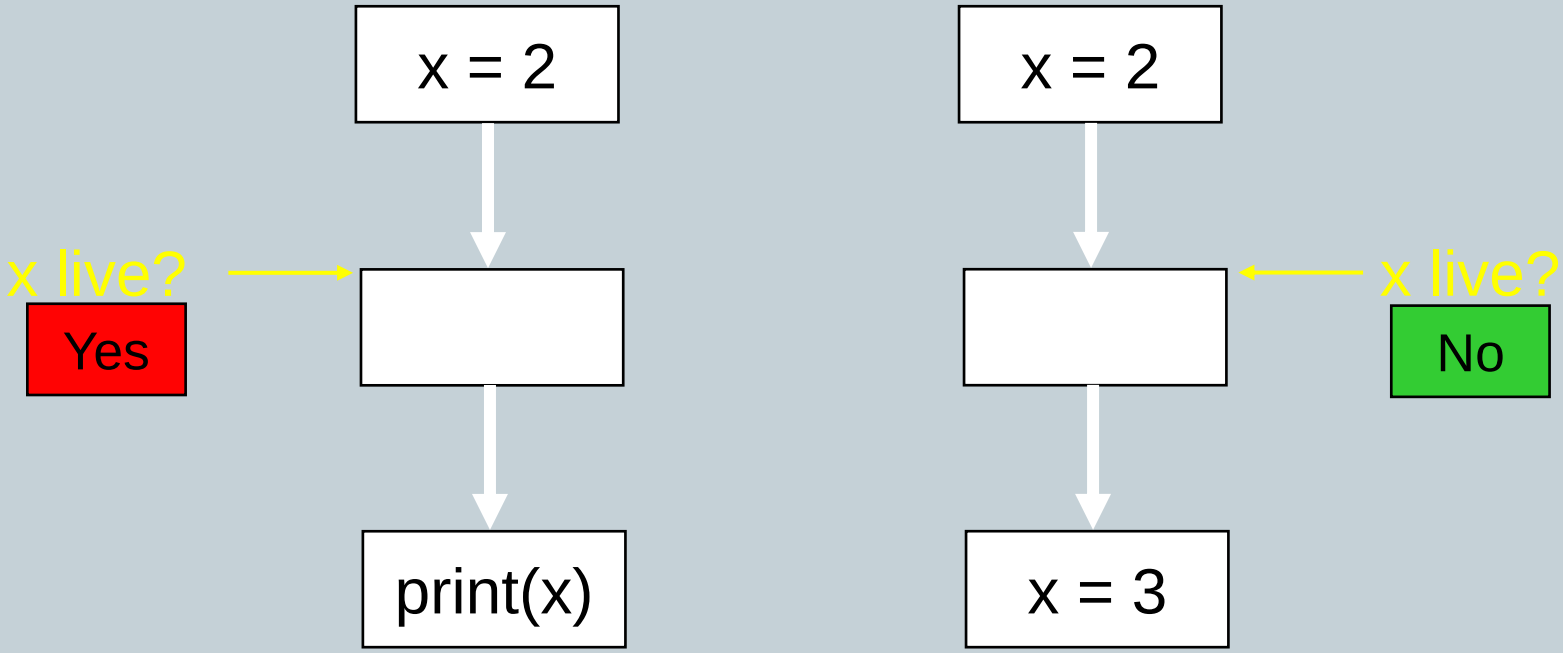


- Lattice tells us how to merge values

Data Flow Analysis Example II

- Do we need the value of variable x?

  Will we ever use the value of x in the future?



- Dataflow analysis can operate on abstract entities

Security Analysis as Data Flow

- Example:

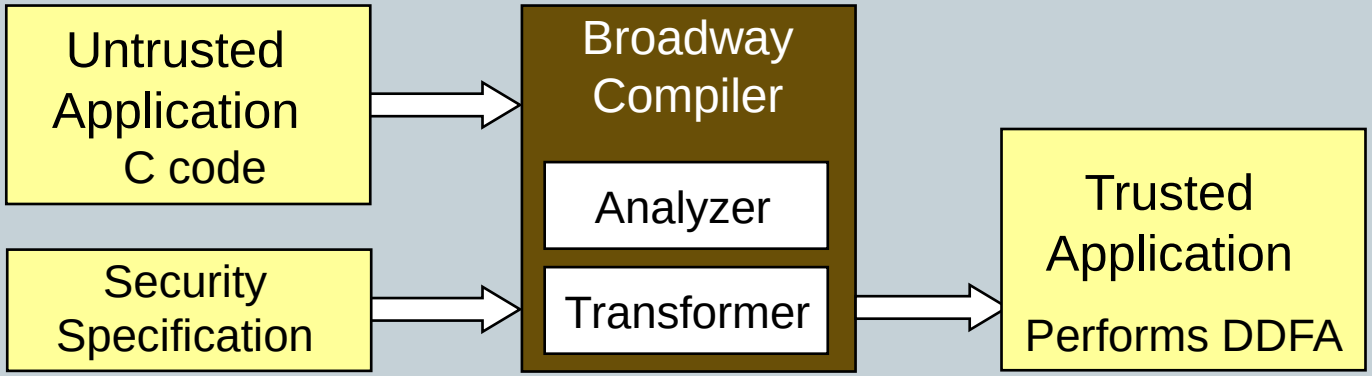
```
int sock;
char buffer[100];
sock = socket(AF_INET, SOCK_STREAM, 0);
read(sock, buffer, 100);
execl(buffer);
```

- Vulnerability: executes any remote command
  - What if this program runs as root?
  - Requirement:

Data from an Internet socket should not specify a program to execute

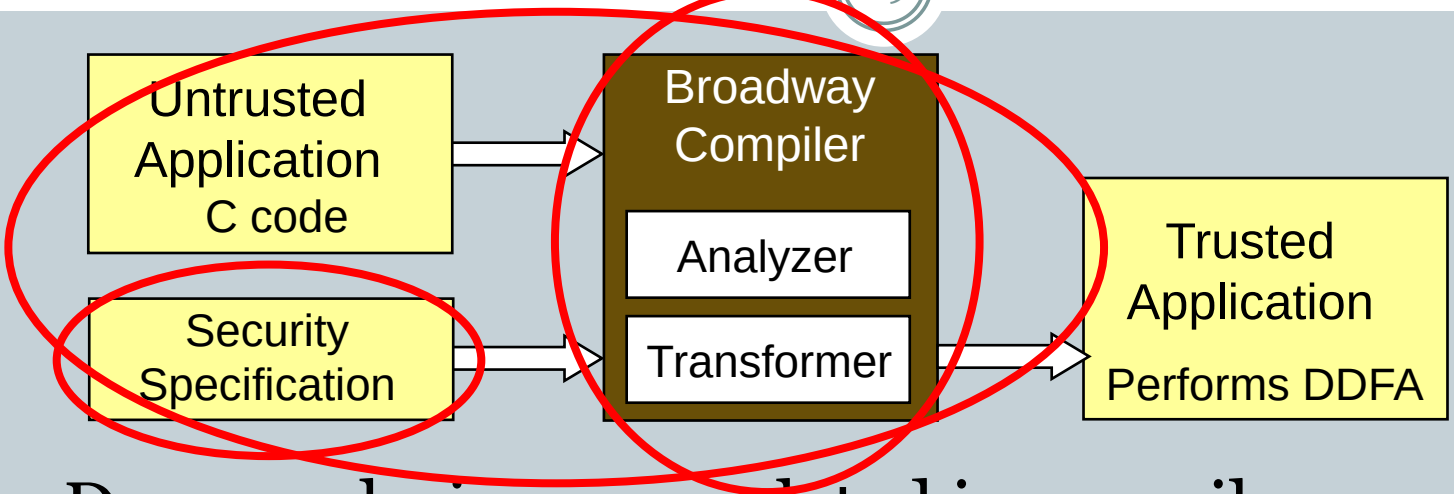
- Typestate analysis:
  - Attach tags to objects to reflect object state
  - Keep tags updated during execution

Deploying DDFA



- Trusted program is instrumented version of the untrusted program
  - Performs Dynamic Data Flow Analysis
  - Enforces typestate security policy

Benefits of Broadway Approach



- Deep analysis encapsulated in compiler
- Specifications written by security expert
  - Can be re-used many times
  - eg. Annotate Standard C library once, can be applied to many C programs
- System administrator simply invokes the compiler

DDFA Example

Inserted Code

```
int v_s, v_b;
```

```
v_s = Tainted;
```

```
v_b = Tainted;
if (v_b!=Tainted)
{
    execl(buffer);
}
```

Original Code

```
int sock;
char buffer[100];
sock = socket(AF_INET, SOCK_STREAM, 0);
read(sock, buffer, 100);
execl(buffer);
```

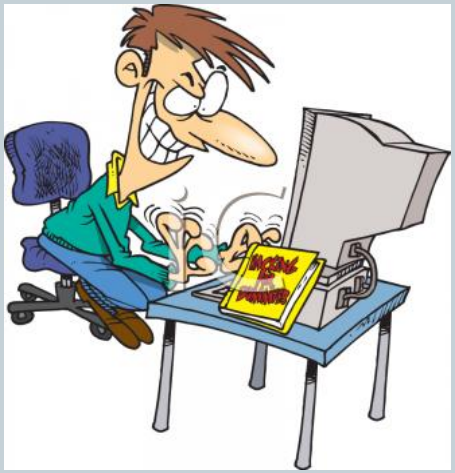
DDFA – Simplified View

DDFA works in three stages:

- Introduction
  - Associates property values to memory objects as they are introduced into a program
- Propagation
  - Tracks the flow of memory objects and their property values throughout the program
- Violation
  - Identifies if a violation occurs at runtime based on the memory objects' property values, which static analysis alone is not able to do

Example 1
Format String Vulnerability

Introduction



Hacker introduces mal-formed printf() format string via web

DDFA marks data entering from the web as “Tainted”

Propagation

```
int sock;
char buf[100];
sock = socket(AF_INET, …);

recv(sock, buf, 100, 0);
```

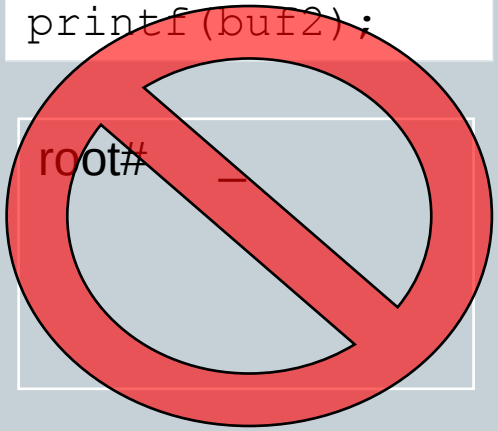
…

```
buf2 = strdup(buf);
```

DDFA tracks the flow of this “Tainted” data throughout the execution

Violation

```
printf(buf2);
```



Tainted string arrives at printf() statement

DDFA flags a runtime violation, preventing the vulnerability from being exploited by the hacker

Example 2
Role Based Access Control

Introduction

Beetle Bailey logs on to Missile system to perform safety checks

DDFA registers him to the system as “grunt” level

Propagation

```
ac_level = authenticate();

...

safety_check();
```

DDFA tracks the flow of all Beetle’s activities throughout the missile system application

Violation

```
launch();
```

Beetle accidentally attempts to invoke launch()
DDFA flags a runtime violation, preventing missile from being launched

Benefits of DDFA

- Application dataflow is tracked at compile and run time
  - Very low runtime overhead (many cases < 1%)
    - Leverages semantic information from policy
  - Complements other security approaches (e.g. Procees Coloring)
  - Configurable error mitigation at run time (e.g. fight through)
- Policy is separate from the source code
  - Removes security concerns when developing new applications
    - Including 3rd party and open-source development
  - Can secure existing legacy applications
  - Requires one additional step in an automated build process

Benefits of DDFA (cont)

- Generality and expressiveness of policy language
  - Can simultaneously defend against multiple security vulnerabilities (i.e. policy elements are composable)
    - (e.g. format string, file disclosure)
  - Possible to solve problems affecting memory-safe languages like Java and C#
    - SQL injection
    - Cross-site scripting
  - Applicable to areas that depend upon semantic information
    - Role based access control
    - Privacy concerns that involve data flow
  - Agile to combat new/future threats

Process Coloring

PURDUE

What is Process Coloring?

- Propagating and logging provenance information ("colors") along OS-level information flows for malware detection and sensitive data protection
- System level inter-process data flow tracking
- User can define what colors are associated in the system

How does PC work?

- Colors are propagated using custom code in the Linux kernel
- Color propagation is logged via the Xen hypervisor
  - Policy decisions can be made based on log info
- Reads to and writes from file descriptors are monitored for color propagation

PC Usage Scenario:
Server-Side Malware

Capability 1:
PC malware alert

"No shell process should have the color of Apache"

Initial coloring

s55sshd

s45named

init → rc → s80httpd

Syscall Log

/etc/shadow

Capability 3:
Color-based log partition for contamination analysis

httpd

netcat

/bin/

Local files

Capability 2:
Color-based identification of malware break-in point

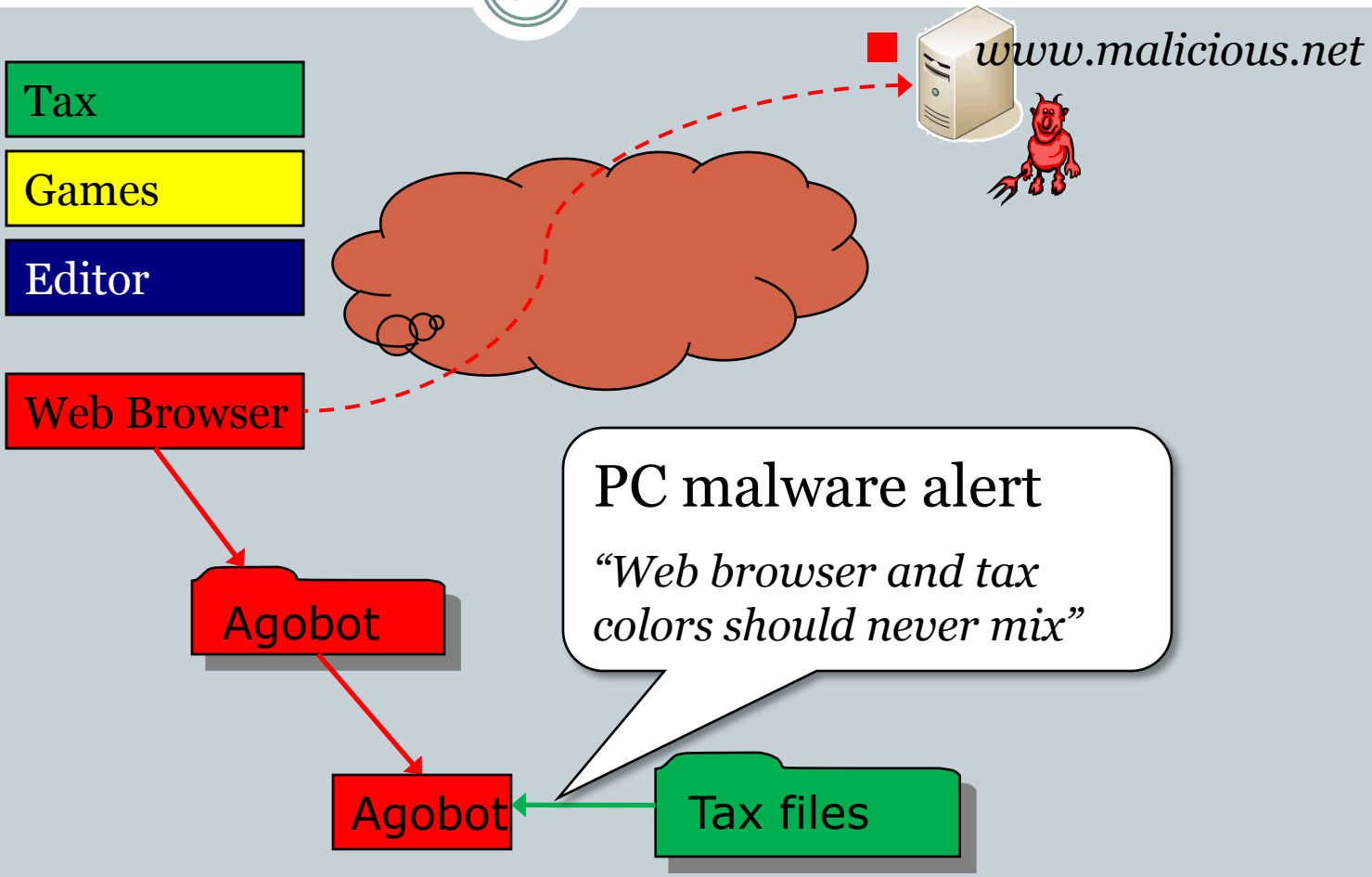
Coloring diffusion

wget

Rootkit

Demo at: *http://friends.cs.purdue.edu/projects/pc/pc-demo.html*

PC Usage Scenario:
Client-Side Malware Attack



Demo at: *http://friends.cs.purdue.edu/projects/pc/files/sinkfile.avi*

“Living Lab” VM: End User’s View

Applications Places System Tue Jul 22, 1:54 PM

Here is a file...

File Edit View Insert Format Security

Send Save Draft Attach Undo Redo Cut Copy

From: John Smith <jsmith@something.com> Signature: None

To: rileyrd@purdue.edu

Subject: Here is a file...

Normal

Hide Attachment Bar 1 Attachment

f1040.pdf
(438K)

Evolution - Outbox (0 unsent) Here is a file...

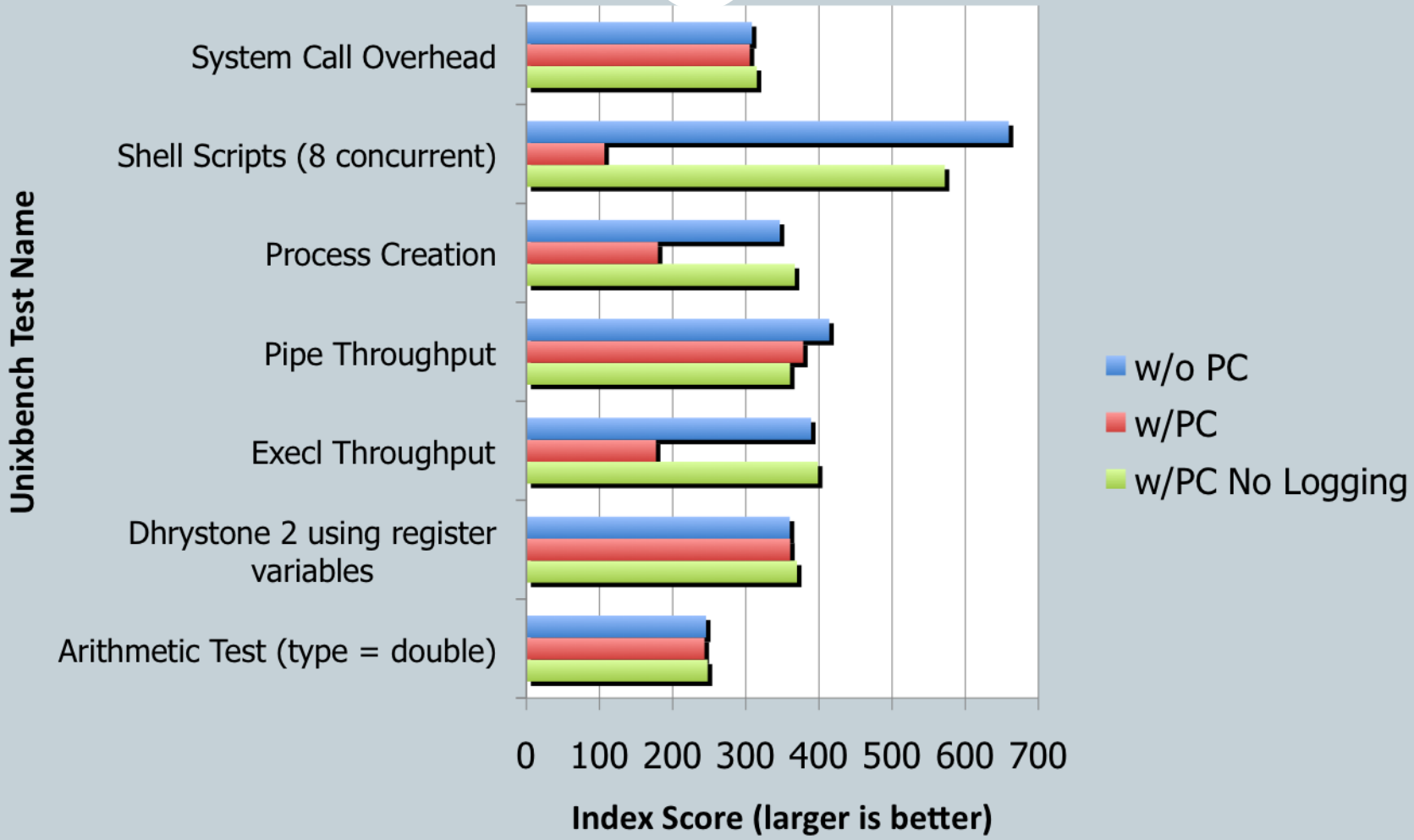
"Living Lab" VM: Administrator's View

ryan@ilovny: /tmp

File Edit View Terminal Tabs Help

```
type=IW dst=8538 pid=3609 p_oc="10" f_oc="10"
type=ID src=8538 name="/[8538]"
type=F src=P3565 dst=P3610 p_oc=""
type=F src=P3608 dst=P3611 p_oc=""
type=IW dst=8387 pid=3609 p_oc="10" f_oc="10"
type=ID src=8387 name="[8387]"
type=F src=P3481 dst=P3612 p_oc=""
type=F src=P3481 dst=P3613 p_oc=""
type=IW dst=8546 pid=3561 p_oc="10" f_oc="10"
type=ID src=8546 name="/[8546]"
type=F src=P3561 dst=P3614 p_oc="10"
type=F src=P3561 dst=P3615 p_oc="10"
type=F src=P3561 dst=P3616 p_oc="10"
type=F src=P3481 dst=P3617 p_oc=""
type=F src=P3481 dst=P3618 p_oc=""
type=IR src=393524 pid=3561 f_oc="40" p_oc="10,40"
type=ID src=393524 name="/home/user/Desktop/docs/f1040.pdf"
type=IW dst=8385 pid=3561 p_oc="10,40" f_oc="10,40"
type=ID src=8385 name="/[8385]"
type=F src=P3481 dst=P3619 p_oc=""
type=F src=P3481 dst=P3620 p_oc=""
type=F src=P3481 dst=P3621 p_oc=""
type=F src=P3481 dst=P3622 p_oc=""
```

Evaluation Metrics – Efficiency



Evaluation with Malware (Agobot, P2P bot…)

ryan@ilovny: /tmp

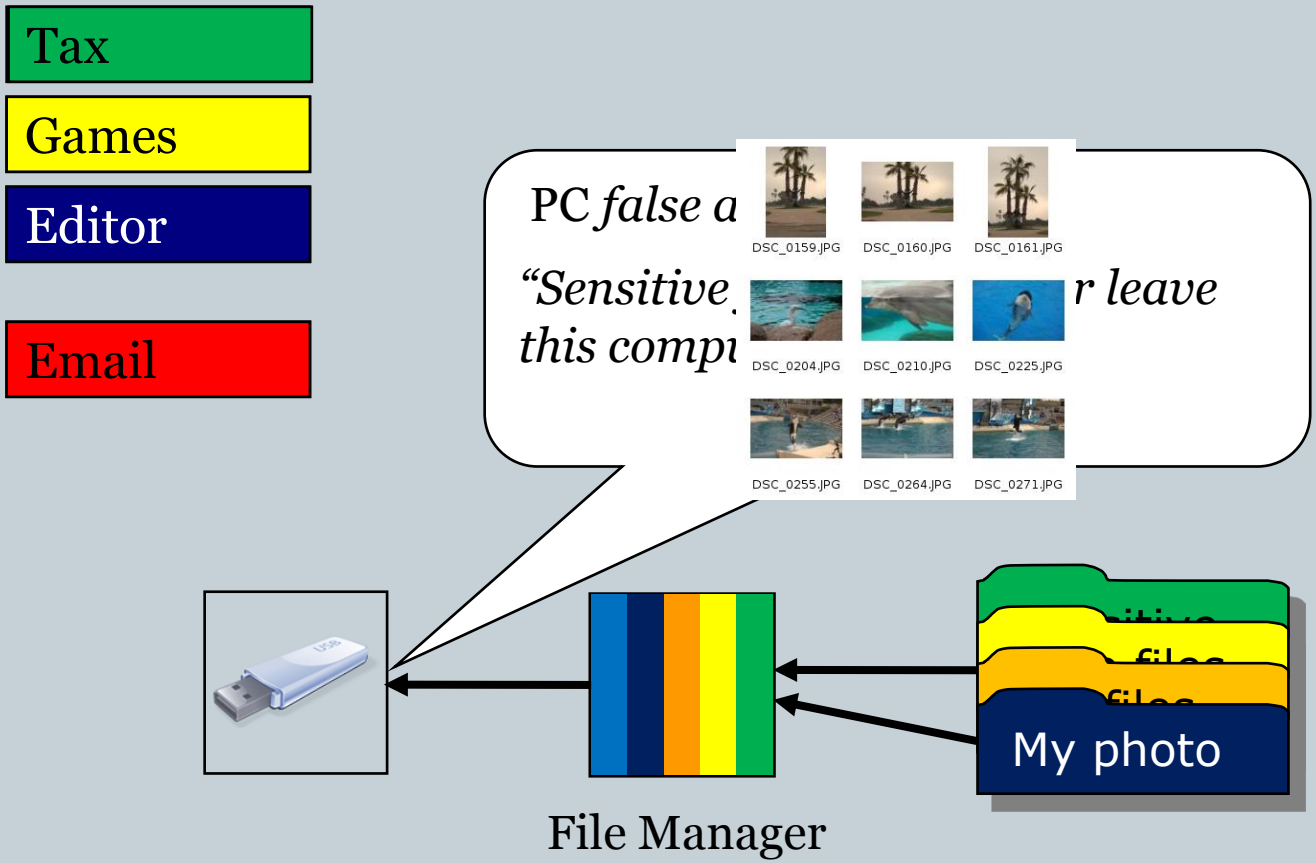
File Edit View Terminal Tabs Help

```
type=ID src=393376 name="/home/user/Desktop/docs/finances.txt"
type=F src=P3297 dst=P3350 p_oc=""
type=E pid=3350 name="bash"
type=IR src=393261 pid=3348 f_oc="20" p_oc="40,20"
type=ID src=393261 name="/home/user/repo/git/ryan.c"
type=F src=P3297 dst=P3351 p_oc=""
type=E pid=3351 name="bash"
type=F src=P3351 dst=P3352 p_oc=""
type=E pid=3352 name="vi"
type=F src=P3352 dst=P3353 p_oc=""
type=E pid=3353 name="sh"
type=IR src=393342 pid=3348 f_oc="1" p_oc="40,20,1"
type=ID src=393342 name="/home/user/.Trash/dsn07-codeinj (copy).pdf"
type=IR src=627318 pid=3348 f_oc="14" p_oc="40,20,1,14"
type=ID src=627318 name="/home/user/pics/dir1/dir2/dir3/img_9995.jpg"
type=IR src=627317 pid=3348 f_oc="13" p_oc="40,20,1,14,13"
type=ID src=627317 name="/home/user/pics/dir1/dir2/img_9993.jpg"
type=IR src=627316 pid=3348 f_oc="12" p_oc="40,20,1,14,13,12"
type=ID src=627316 name="/home/user/pics/dir1/img_9992.jpg"
type=IR src=393615 pid=3348 f_oc="10" p_oc="40,20,1,14,13,12,10"
type=ID src=393615 name="/home/user/agobot/agobot3"
type=IR src=527243 pid=3348 f_oc="11" p_oc="40,20,1,14,13,12,10,11"
type=ID src=527243 name="/usr/lib/openoffice/program/soffice.bin"
```

Putting it all together

SWRI

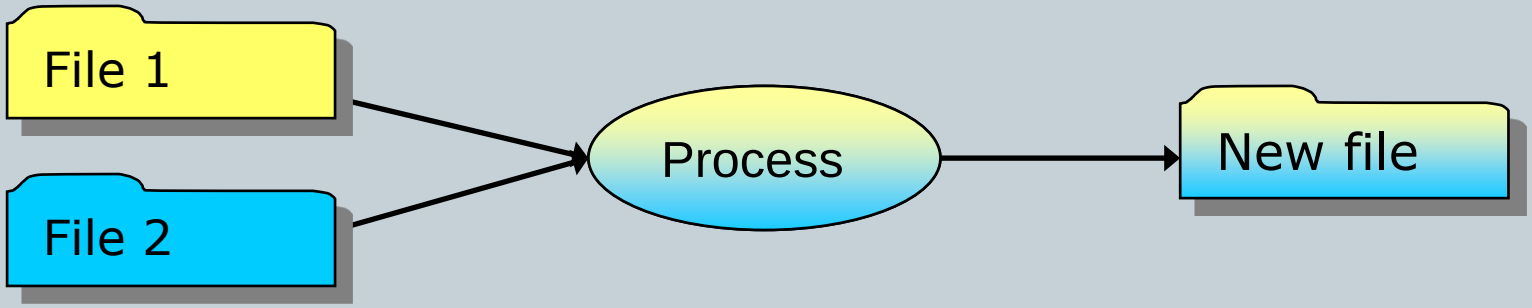
A Motivating Scenario



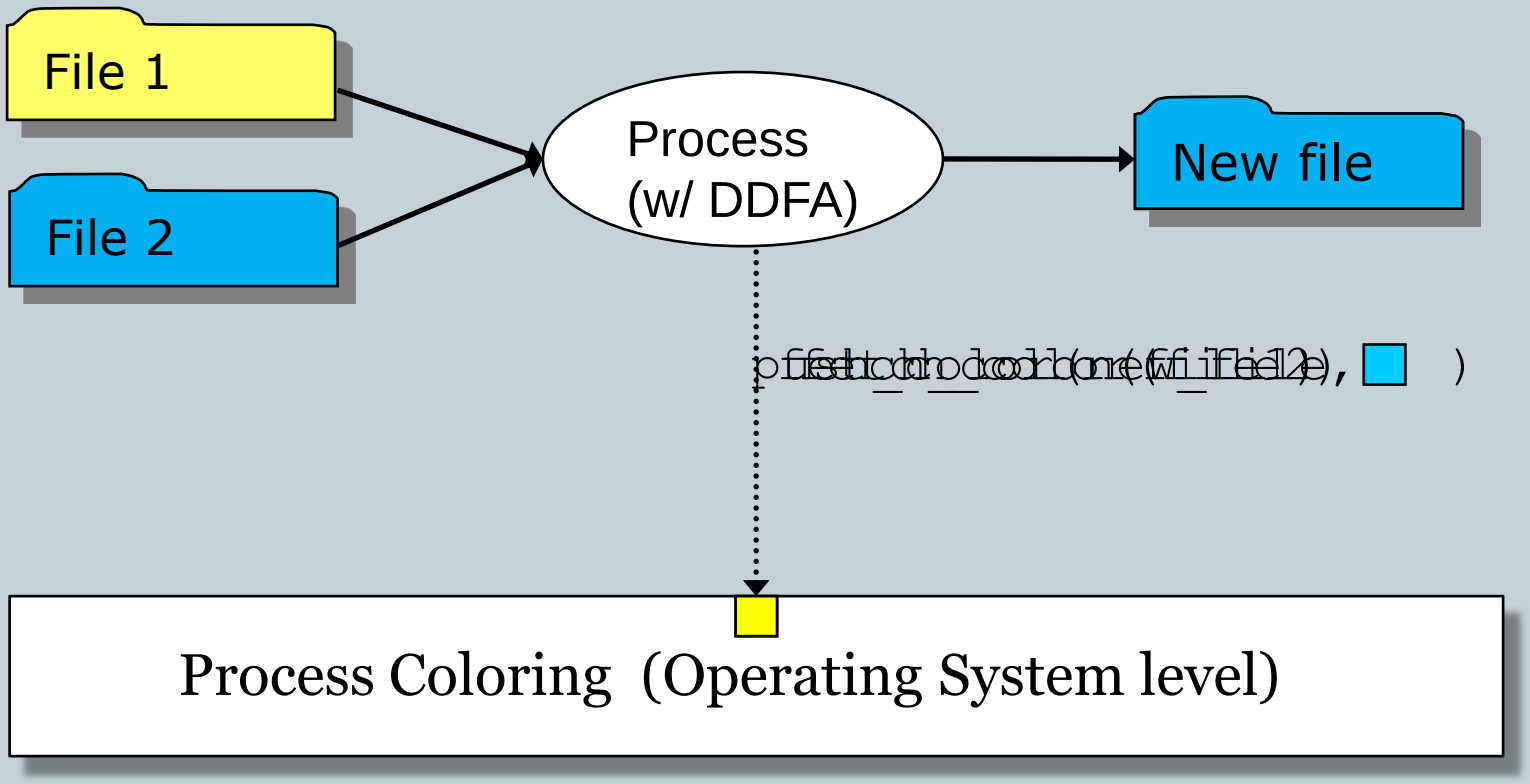
PC or DDFA Alone Cannot Solve It

- PC
  - ☹ Process-level information flow treating processes as blackboxes
  - ☹ Overly conservative color tainting
  - ☺ Color tainting across processes
- DDFA
  - ☹ Language-level information flow confined within one process
  - ☹ Not aware of colors across the system
  - ☺ Fine-grain data flow tracking within a process

Example: *Without* "PC+DDFA" Integration

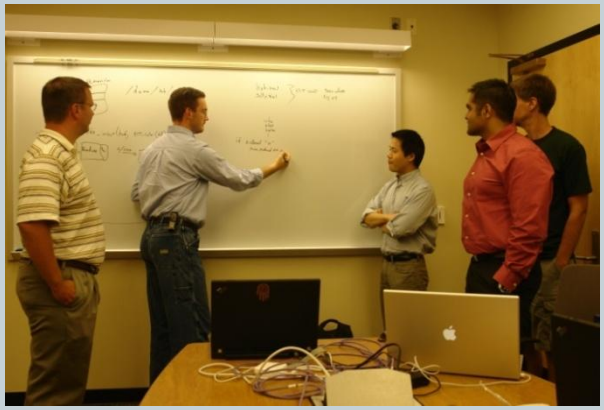


Example: *With* "PC+DDFA" Integration

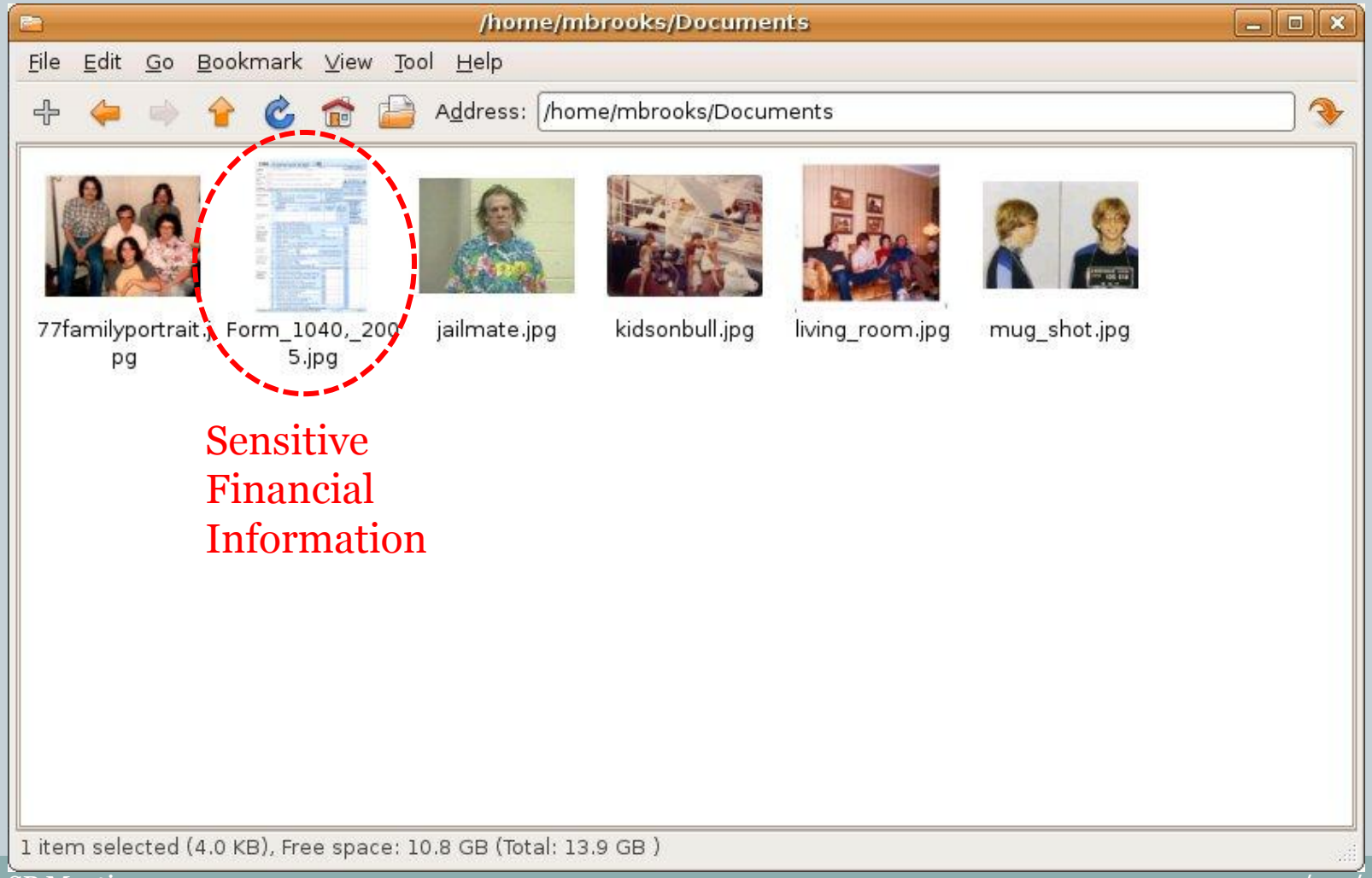


Example Scenario Tasks

- SWRI+UTexas
  - Making DDFA color-aware
  - Instrumenting a real-world file manager **`PCManFM`** with DDFA capability
- Purdue
  - Implementing **`fetch_color()`** and **`push_color()`** in PC
  - Testing instrumented **`PCManFM`** in living lab VM
- Integration Meeting
  - September 8th, 2008 SwRI visited Purdue



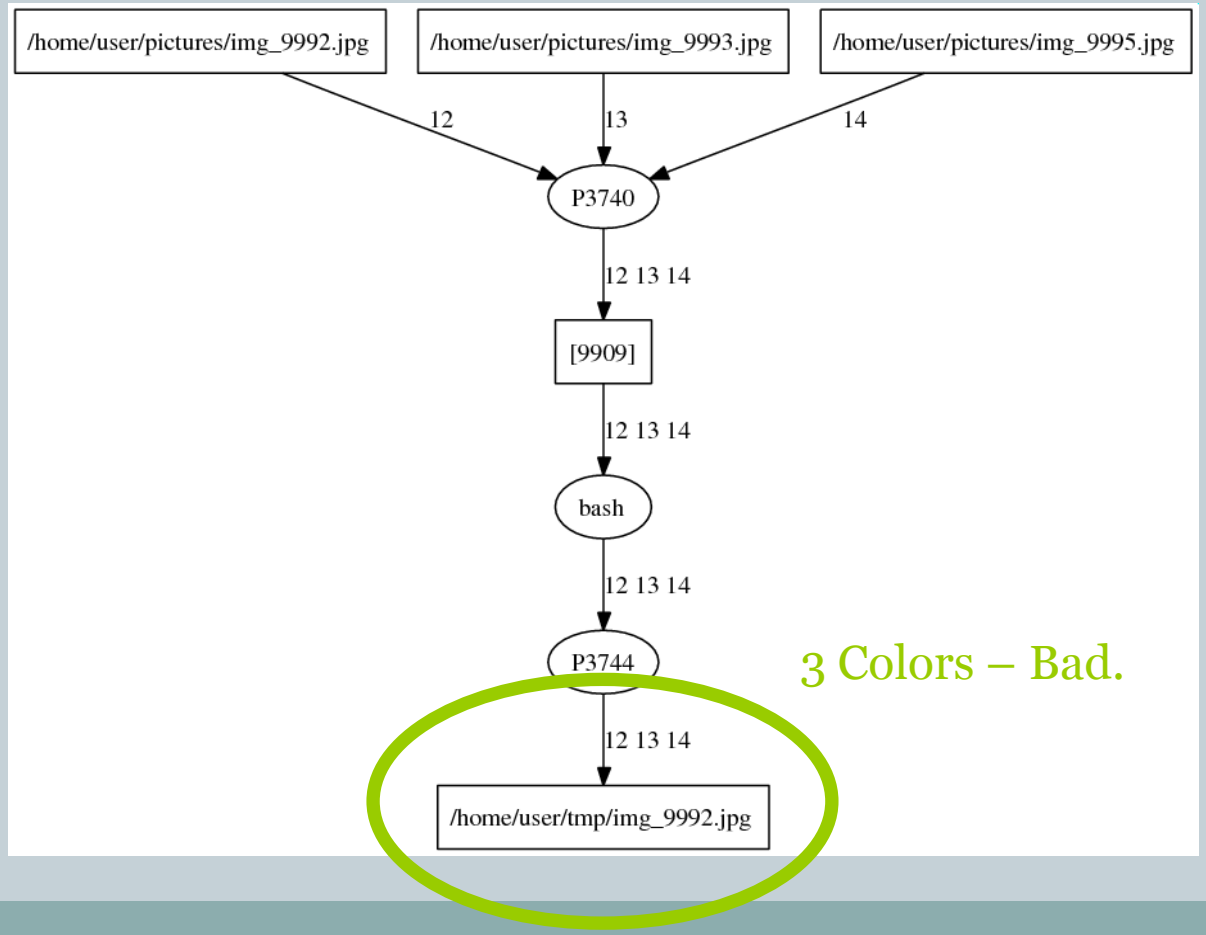
PCManFM



Sensitive Financial Information

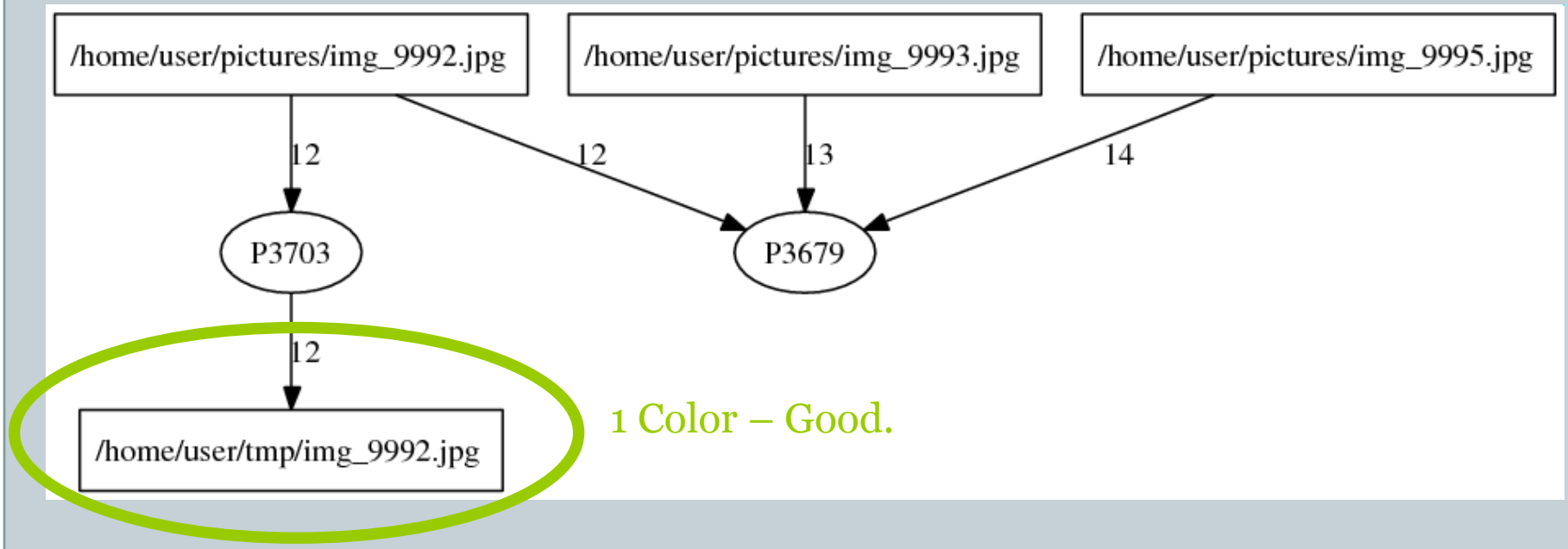
Flow Graphs

- Process Coloring *Without* DDFA



Flow Graphs

- Process Coloring *With* DDFA



Summary

- Neither DDFA nor PC solves the entire system level security problem
- DDFA = intra-process data flow tracking
- PC = inter-process data flow tracking
- Together DDFA and PC implement policy-driven system data flow tracking