Kernel Level Vulnerabilities

Behind the Scenes of the 5th Argus Hacking Challenge

Chaos Communication Congress 2001

Originally presented on Black Hat Briefings 2001

Last Stage of Delirium Research Group

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The Last Stage of Delirium Research Group

- The non-profit organization, established in 1996,
- research activity conducted as the LSD is not associated with any commercial company,
- four official members,
- all graduates (M.Sc.) of Computer Science from the Poznań University of Technology, Poland
- for the last six years we have been working as Security Team at Poznań Supercomputing and Networking Center.

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Our fields of activity

- Continuous search for new vulnerabilities as well as general attack techniques,
- analysis of available security solutions and general defense methodologies,
- development of various tools for reverse engineering and penetration tests,
- experiments with distributed host-based Intrusion Detection Systems with active protection capabilities,
- other security related stuff.

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Presentation overview

- General introduction
- Basics of Pitbull Foundation Intrusion Prevention System
- About 5th Argus Hacking Challenge
- The ldt kernel level vulnerability
- The specified phases of the attack against system with security enhanced by Pitbull Foundation
- Technical details of successful proof of concept code
- Summary and final remarks

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Motivations

- The main goal of this demonstration is to present the technical details of successful exploiting kernel level vulnerabilities
- The special emphasis will be put on potential consequences of such errors
- The Argus Hacking Challenges as an interesting case study of such consequences
- There is no such thing like 100% secured system
- The system can be considered secure only in the specific place at the specific moment

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Pitbull Foundation

Intrusion Prevention System

- Software enhancement to the operating system that is based on the Trusted Operating Systems (TOS) technology
- It got B1 security evaluation under the Information Technology Security Evaluation Criteria (ITSEC)
- It was approved for governmental use by NSA and DoD
- It has never been hacked before...

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Pitbull Foundation features

- Removal of superuser privileges
- Least privilege
- Information compartmentalization and Mandatory Access Control (MAC)
- Role compartmentalization
- Kernel-level enforcement

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Privileges

- They are attributes of a process or file system object that define what security relevant actions a specific code is allowed to perform
- In a standard UNIX OS root inhibits all power in the system
- In Pitbull root privileges are divided into many sub-privileges (**PV_DAC_R**, **PV_FS_MOUNT**,...)
- There are new privileges added to the system (**PV_MAC_W**, **PV_PROC**,...)

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The least privilege principle

- A process or executable should only have the minimum necessary privileges needed for the performance of its tasks
- A user should only have the authorizations which are required for the performance of his duties
- Privileges are enabled or disabled around the smallest section of code that requires them

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Information Compartmentalization

- Standard Unix operating systems implement access control with the use of Discretionary Access Control (DAC): permission bits and ACLs
- Mandatory Access Control (MAC) is a mechanism providing information compartmentalization in TOS
- Unlike standard DAC, MAC restrictions cannot be overruled by a root-owned process

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Information Compartmentalization (2)

- Every object on the system, including both files and processes, has a sensitivity label (SL)
- There are two components of a sensitivity label: *classification* and *compartments*
- Classification is a hierarchical component of SL. It defines sensitivity of information
- Compartments are non hierarchical components of sensitivity labels. They define sets of information categories

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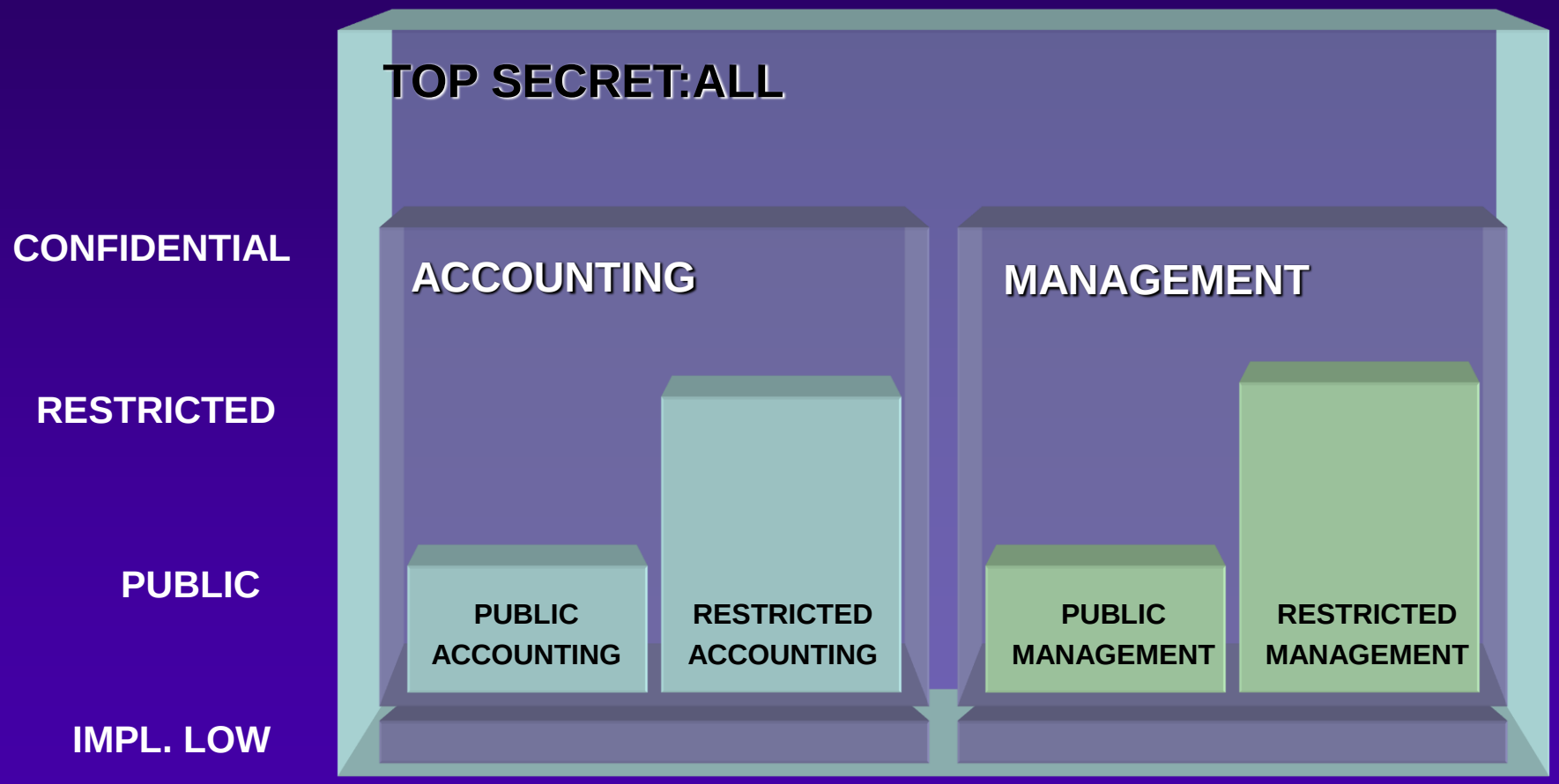
Information Compartmentalization (3)



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Information Compartmentalization (4)

- A process cannot open a file for reading unless the SL of the process dominates the SL of the file
- A process cannot open a file for writing unless the SL of the process equals the SL of the file
- Unless a process has the privilege needed to change an SL, the process cannot change its own SL or the SL of any process or file on the system

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Role Compartmentalization (Authorizations)

- A combination of privileges and authorizations is used to enforce role compartmentalization
- Authorizations are assigned to users (privileges to processes). They are required in order to use privileges
- If a user is not authorized for a privilege, he will not be able to use that privilege even if he is permitted to execute a privileged file

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Kernel Level Enforcement

- Security decisions are made at the operating system kernel level
- The security decisions are made as close as possible to the resources being protected
- The system is more secure than any combination of user-level or application-level security
- The standard UID 0 checks are replaced with more specific and more targeted privilege checks
- Root exploits are no longer useful to intruders

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LSD comments on Pitbull Foundation

+ Provides additional kernel level protection
+ It is based on TOS technology (proved mathematical security models)
+ Protects against classical user level attacks

but...

- It is potentially open to new threats
- Some of its features seem to be overused
- Tight configuration of the system is very difficult. It requires a lot of experience and work.

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5th Argus Hacking Challenge

Coincided with Infosecurity Europe 2001 Exhibition, held in London, 20-25 April 2001.

The rules:

- Hack the system secured with Pitbull Foundation 3.0 MU4 and servicing the web pages of two fictional companies: *Xtype* and *XCursion*
- Do it within 5 days time
- In a case of success reveal how it was achieved
- Get the prize of 50 000 USD!

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Challenge system configuration

- Solaris 7 x86 with Pitbull Foundation 3.0 and .comPack (web protection) installed
- Partially secured OS (patches applied, the number of services decreased, *set-user-id* bits removed from many system binaries)
- Remote shell access via TSSH service to the public *webhack* account
- Separate and disjoint compartment definitions for user *webhack*, *httpd* server, *xtype* and *xcursion* web pages directories
- ASN rules for network protection

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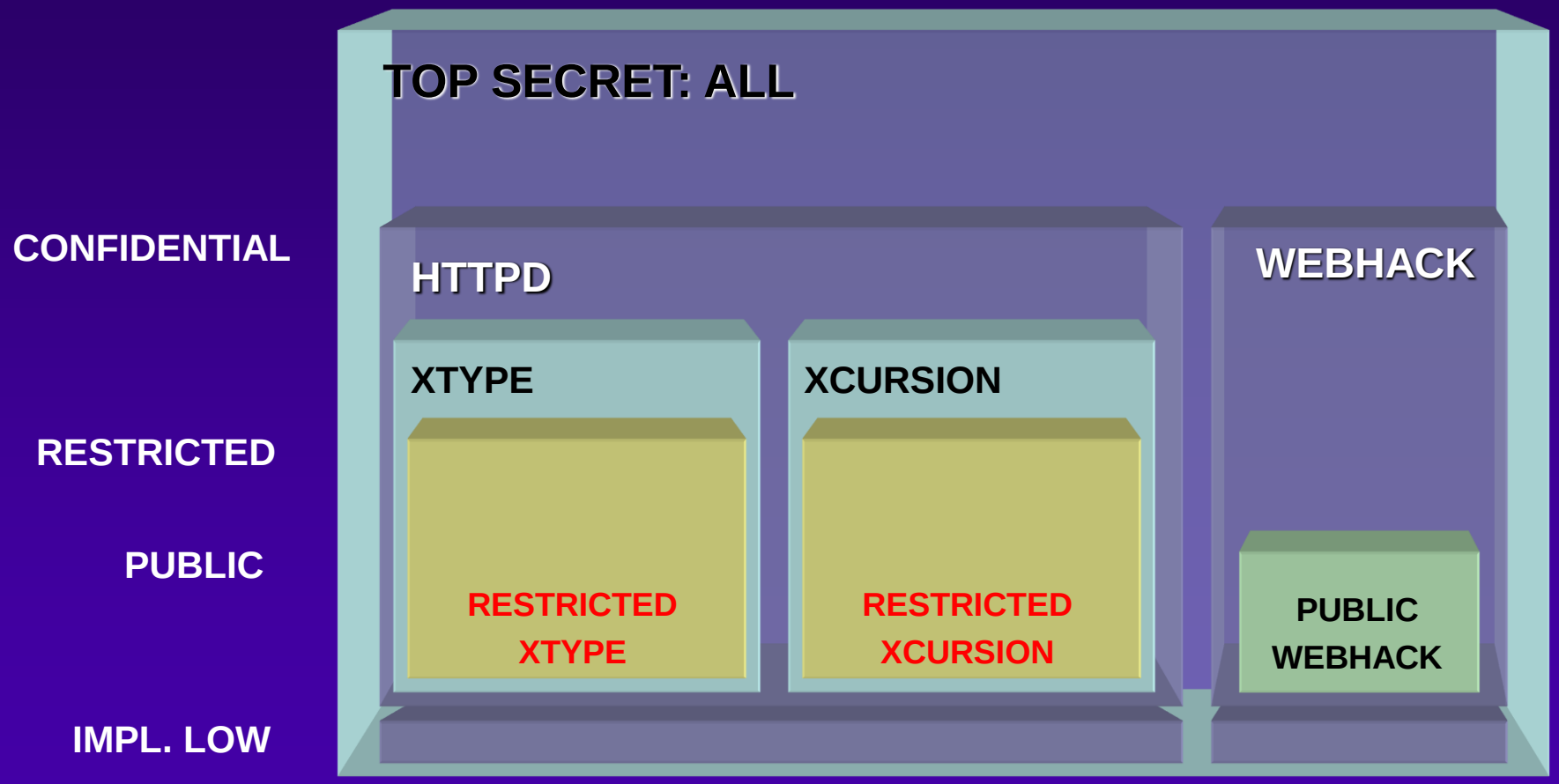
Simplified challenge system configuration (2)



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Challenge system configuration (3) XTYPE

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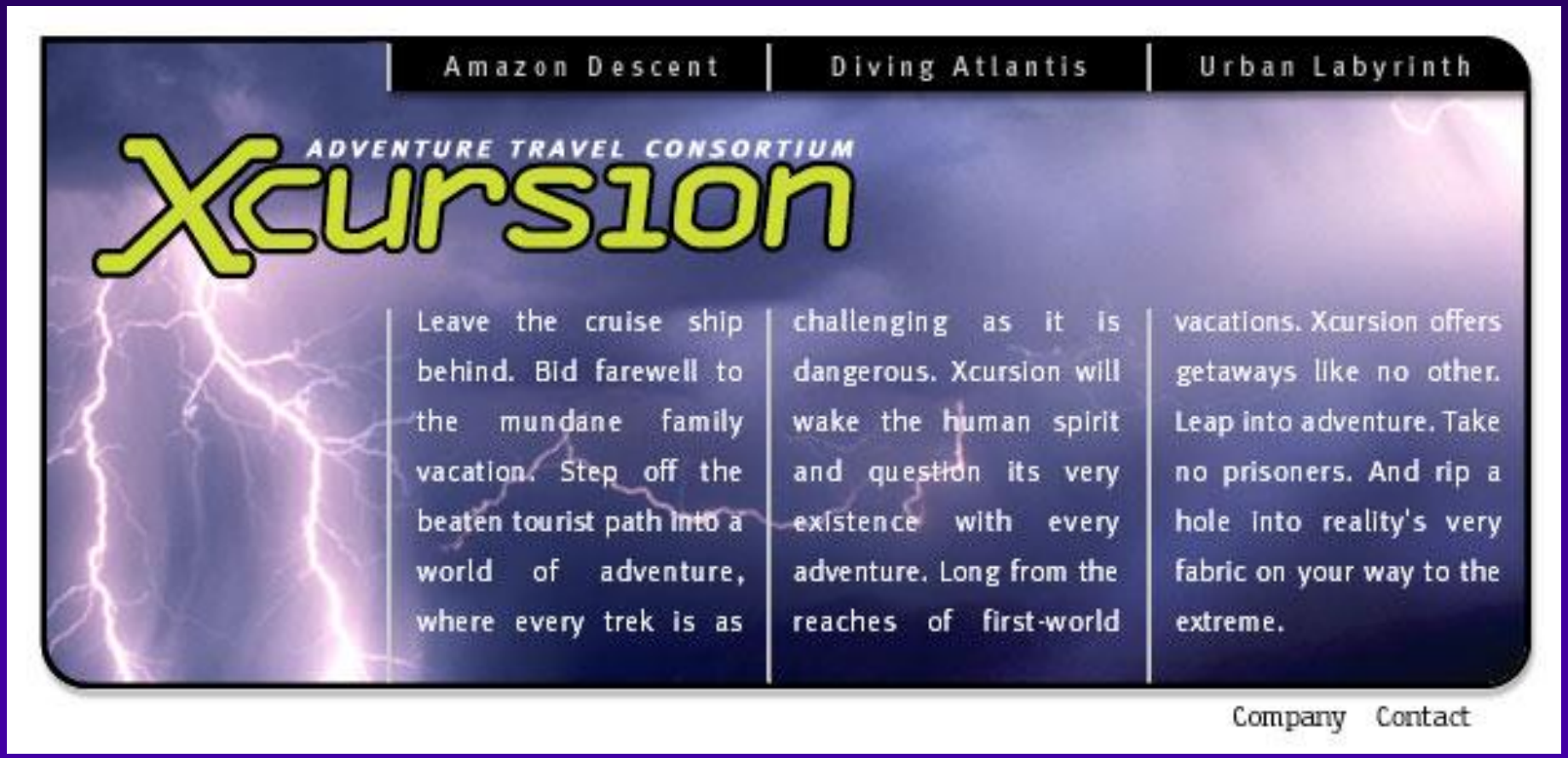
Challenge system configuration (4) XCURSION



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The weapon: ldt bug

- Specific to x86 architecture and OS protection mechanisms provided by x86 family of processors
- Kernel level vulnerability that allows user mode processes to install call gates in their Local Descriptor Table
- Installed call gate could be an entry point to 0 protection level, thus it would allow code execution at the OS kernel level
- Uncommon and tricky to exploit

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ldt bug (2) - destroying the myth

- First reported in a NetBSD Security Advisory in January 2001 (reported by Bill Sommerfeld)
- According to the advisory the following operating systems were vulnerable: Solaris, NetBSD / OpenBSD
- We found its existence in SCO Unixware and SCO OpenServer
- At the time of a challenge Solaris x86 as well as Pitbull were still vulnerable (!)
- Is it a Solaris or Pitbull's bug ?

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Attack phases

- The attack was performed within 24 hours time and it consisted of several phases, reflecting major modifications done to the ldt proof of concept code
- During each of the phase some new idea was tried
- There were some mistakes done, that fortunately did not lead to the system reboot (could be treated as an action against the Challenge rules)

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Phase 0 (09:00 CET, Friday)

- Finding information about the Challenge on a security news portal
- Installation of Pitbull 3.0 MU4 on a local machine for the “know your enemy” purposes
- System configuration and tuning in order to reflect the challenge conditions
- Verification of the ldt bug on the testbed system
- Development of fully operational proof of concept code for ldt bug

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Phase 1 (18:00 CET, Friday)

- Login to the webhack account through SSH
- Verification of user webhack privileges
- Verification of Pitbull settings for user webhack
- General look around the system
  - local vulnerabilities
  - ASN network protection
- Verification of the ldt bug on a challenge system

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Phase 1: Initial Privileges

Subject:
`LSD hunter process`

uid: webhack
sl: PUBLIC WEBHACK
privs: none

Access checks: **READ / WRITE**

MAC: compare SUB SL with OBJ SL

WEBHACK ?? XTYPE
compartments disjoint

READ FAILED WRITE FAILED

DAC: none

File system object:
`/www/xtype/htdocs/index.html`

MAC

Sensitivity label

Classification	*Compartments*
RESTRICTED	XTYPE

DAC

Rights mask

Owner			*Group*			*Other*		
R	W		R			R		

owner: **xtype**

group: **xtype**

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Phase 2 (20:00 CET, Friday)

- Application of Solaris x86 ldt proof of concept code to the challenge system
- Gaining standard root user privileges (uid=0)
- Playing with the new set of privileges (root has no power in the system)

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Phase 2: Gaining standard root user privileges (uid=0)

Subject:
`LSD hunter process`

uid: root ✓
sl: PUBLIC WEBHACK
privs: none

Access checks: **READ / WRITE**

MAC: compare SUB SL with OBJ SL

WEBHACK ?? XTYPE
compartments disjoint

READ FAILED WRITE FAILED

DAC: none

File system object:
`/www/xtype/htdocs/index.html`

MAC

Sensitivity label

Classification	*Compartments*
RESTRICTED	XTYPE

DAC

Rights mask

Owner			*Group*			*Other*		
R	W		R			R		

owner: **xtype**

group: **xtype**

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Phase 3 (21:00 CET, Friday)

- Preliminary attempts to bypass MAC protection
- Setting the *classification* component of the user webhack's effective SL to "TOP SECRET"
- Getting the highest information access level in the WEBHACK compartment

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Phase 3: Getting TOP SECRET classification

Subject:
`LSD hunter process`

uid: root ✓
sl: TOP SECRET ✓ **WEBHACK**
privs: none

Access checks: **READ / WRITE**

MAC: compare SUB SL with OBJ SL

WEBHACK ?? XTYPE
compartments disjoint

READ FAILED WRITE FAILED

DAC: none

File system object:
`/www/xtype/htdocs/index.html`

MAC

Sensitivity label

Classification	*Compartments*
RESTRICTED	XTYPE

DAC

Rights mask

Owner			*Group*			*Other*		
R	W		R			R		

owner: **xtype**

group: **xtype**

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Phase 4 (22:30 CET, Friday)

- Setting the *classification* component of the user webhack's effective SL to "TOP SECRET"
- Setting the *compartments* component of the user's SL to ALL
- Obtaining the highest information access level in the protected system (read access to all its objects)
- Writing to target objects is denied

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Phase 4: Getting TOP SECRET classification in ALL compartments

Subject:
`LSD hunter process`

uid: root ✓
sl: TOP SECRET ✓ ALL ✓
privs: none

Access checks: **READ / WRITE**

MAC: compare SUB SL with OBJ SL

TS ALL > RESTRICTED XTYPE
RESTRICTED XTYPE !> TS ALL
subject and object SL are not equivalent

READ ACCEPTED **WRITE FAILED**

DAC: compare uid with object owner
check right mask

root != xtype (users differ)
other[READ]=R

READ ACCEPTED

File system object:
`/www/xtype/htdocs/index.html`

MAC

Sensitivity label

Classification	*Compartments*
RESTRICTED	XTYPE

DAC

Rights mask

Owner			*Group*			*Other*		
R	W		R			R		

owner: **xtype**

group: **xtype**

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Phase 5 (04:00 CET, Saturday)

- Setting the *classification* component of the user webhack's effective SL to "RESTRICTED"
- Setting the *compartments* component of the user's SL to XTYPE
- Obtaining read access level in the XTYPE compartment
- Writing to target objects is still denied

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Phase 5: Getting RESTRICTED classification in XTYPE compartment

Subject:
`LSD hunter process`

uid: root ✓
sl: RESTRICTED ✓ XTYPE ✓
privs: none

Access checks: **READ / WRITE**

MAC: compare SUB SL with OBJ SL

RESTRICTED XTYPE = RESTRICTED XTYPE
subject and object SL are equivalent

READ ACCEPTED WRITE ACCEPTED

DAC: compare uid with object owner
check right mask

root != xtype (users differ)
other[READ]=R, other[WRITE] = 0

READ ACCEPTED WRITE FAILED

File system object:
`/www/xtype/htdocs/index.html`

MAC

Sensitivity label

Classification	*Compartments*
RESTRICTED	XTYPE

DAC

Rights mask

Owner			*Group*			*Other*		
R	W		R			R		

owner: **xtype**

group: **xtype**

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Phase 6 (05:00 CET, Saturday)

- Setting the *classification* component of the user webhack's effective SL to "RESTRICTED"
- Setting the *compartments* component of the user's SL to XTYPE
- Setting *uid* of a process to *xtype* user
- Obtaining full access level (read and write) in the XTYPE compartment

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Phase 6: Getting RESTRICTED classification in XTYPE compartment and uid=xtype

Subject:
`LSD hunter process`

uid: xtype ✓
sl: RESTRICTED ✓ XTYPE ✓
privs: none

Access checks: **READ / WRITE**

MAC: compare SUB SL with OBJ SL

RESTRICTED XTYPE = RESTRICTED XTYPE
subject and object SL are equivalent

READ ACCEPTED WRITE ACCEPTED

DAC: compare uid with object owner
check right mask

xtype = xtype (user is the owner)
other[READ]=R, owner[WRITE] = W

READ ACCEPTED WRITE ACCEPTED

File system object:
`/www/xtype/htdocs/index.html`

MAC

Sensitivity label

Classification	*Compartments*
RESTRICTED	XTYPE

DAC

Rights mask

Owner			*Group*			*Other*		
R	W		R			R		

owner: **xtype**

group: **xtype**

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Phase 7 (07:00 CET, Saturday)

- Setting ALL process privileges (minimum, maximum, limited and effective sets)
- Obtaining full access level (read and write) to the protected system, regardless of the DAC and MAC settings
- Historically, this was the way how the Challenge system was hacked :-)

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Phase 7: Setting all privileges for given process

Subject:
`LSD hunter process`

uid:	**root**
sl:	**PUBLIC WEBHACK**
privs:	**PV_ROOT* PV_SU*** ✓

Access checks: **READ/WRITE**

MAC: checking for privileges

PV_ROOT* present

READ ACCEPTED WRITE ACCEPTED

DAC: checking for privileges

PV_ROOT* present

READ ACCEPTED WRITE ACCEPTED

File system object:
`/www/xtype/htdocs/index.html`

MAC

Sensitivity label

Classification	*Compartments*
RESTRICTED	**XTYPE**

DAC

Rights mask

Owner			*Group*			*Other*		
R	**W**		**R**			**R**		

owner: **xtype**

group: **xtype**

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Defaced web page

XTYPE

ATTENTION!!!
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Defaced web page (2)

XCURSION

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Technical details

This part covers:

- kernel memory protection overview
- how is Pitbull integrated with Solaris x86 kernel ?
- what is x86 ldt bug ?
- why does this bug affect Pitbull product ?

... and finally:

- brief description of how to successfully exploit x86 **ldt** vulnerability in Solaris 7/8 x86 operating system enhanced with Argus Pitbull Foundation 3.0 MU4+ and Web Protection .comPack products

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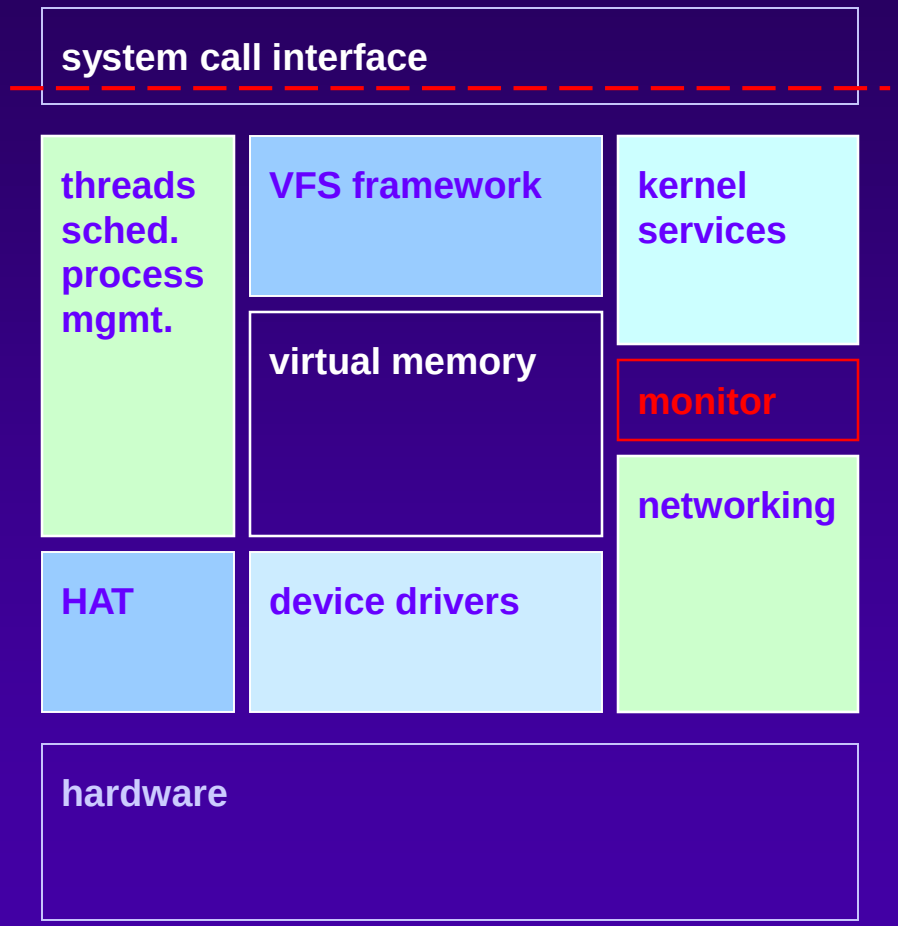
Pitbull protected kernel overview



All critical system actions pass through Argus **Reference Monitor** Module

At least system call layer is intercepted

Theoretically Pitbull has a possibility to control and successfully block any operation initiated by user programs

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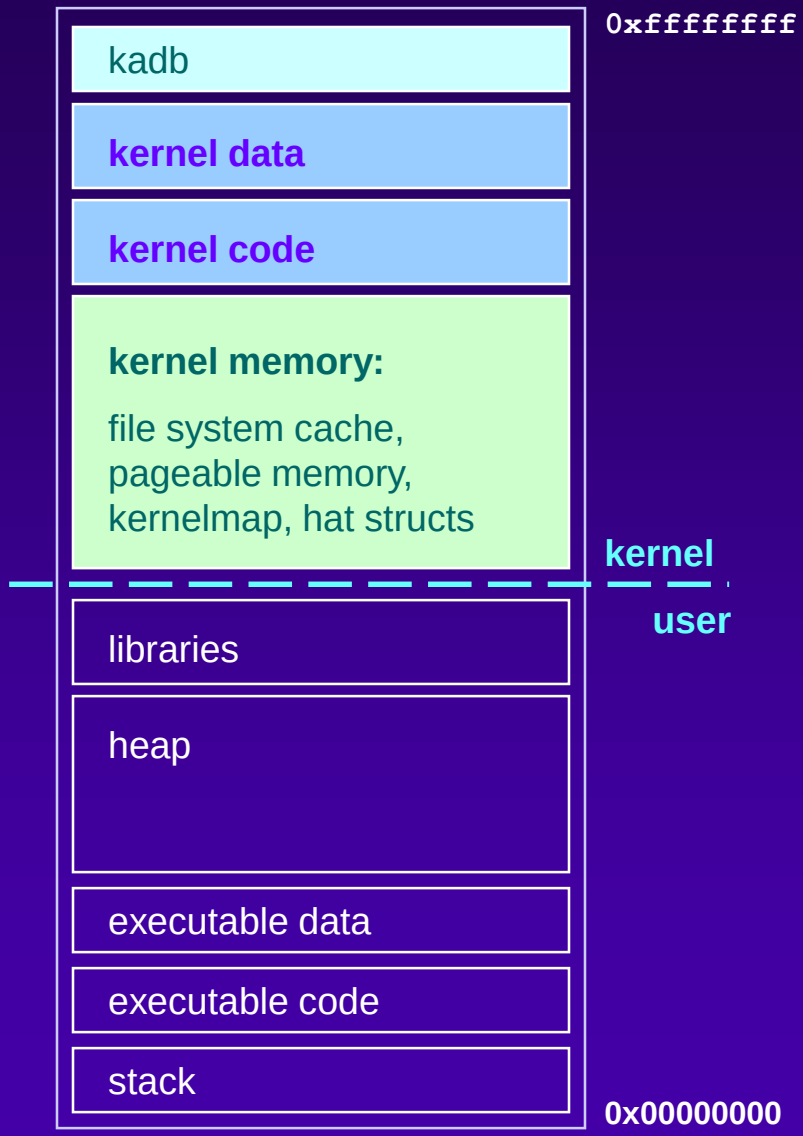
Kernel virtual address maps



Process virtual address space is divided to kernel and user space

Advantages:

- No context switch occurs when transferring control from user to kernel space
- Kernel have direct access to whole user memory
- Kernel can easily distinguish to what memory space a given address belongs to

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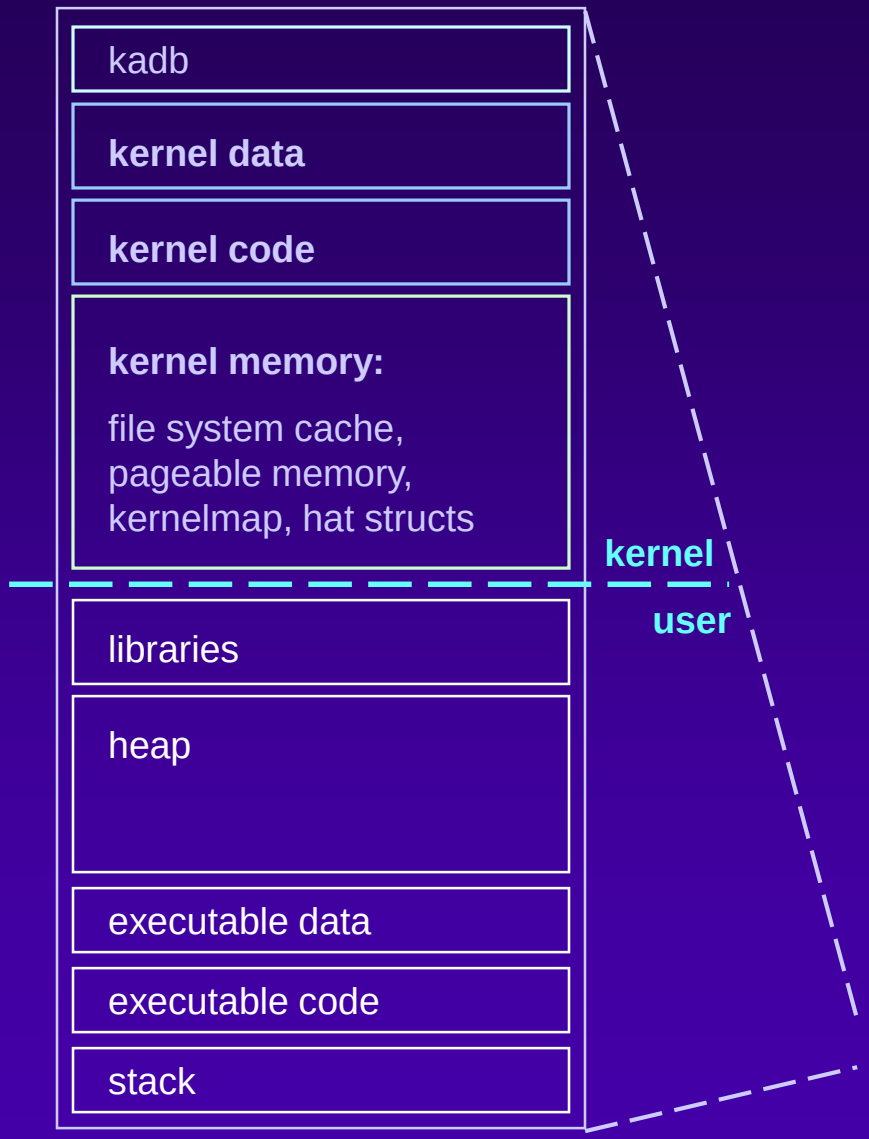
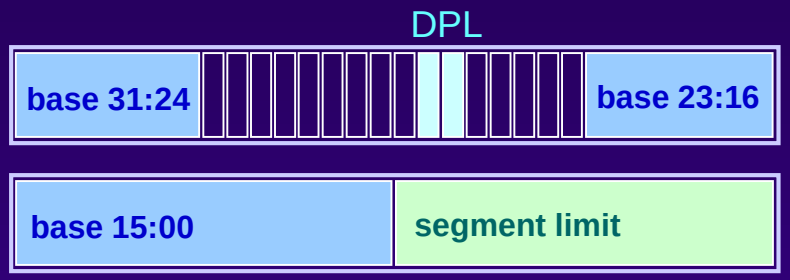
Memory protection



Code Segment Descriptors



In Solaris system, sensitive kernel data and code is protected on a **page level basis**

Process, while in kernel as well as in user mode, uses segment selectors that cover the whole 4GB virtual address space:

```
KCSSEL,KDSSEL:  RPL=0, DPL=0
UCSSEL,UDSSEL:  RPL=3, DPL=3
```

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Processes accessing kernel services

To provide sufficient level of control while accessing code segments with different privilege levels, processors use special set of descriptors, called *gate descriptors*

There are four main types of such descriptors:

- *task gates* connected with task management
- *trap gates* for exceptions handling
- *interrupt and* ***call gates*** usually used to provide interface for accessing more privileged protection levels to user applications operating at the lower ones

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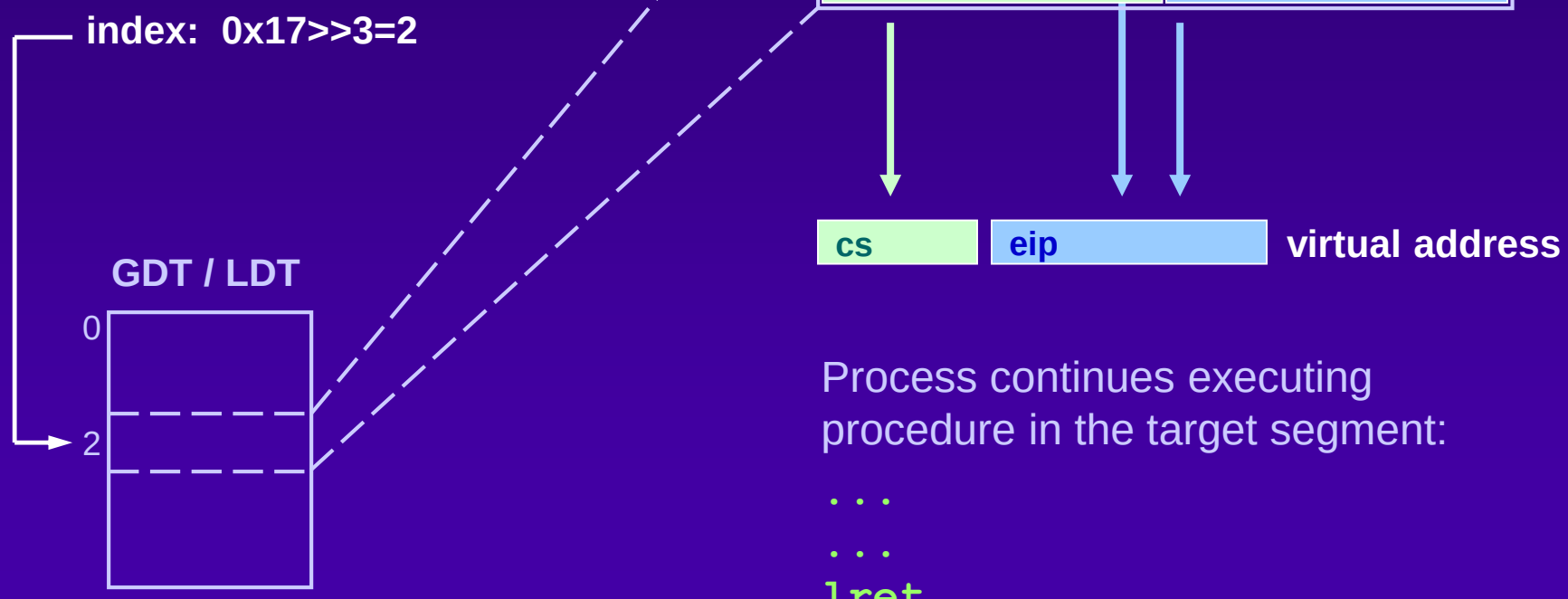
x86 call gate mechanism

Process in user mode:

```
...
lcall $0x17,$0x00000000
```

Processor executes
far inter-segment call instruction



Process continues executing
procedure in the target segment:

```
...
...
lret
```

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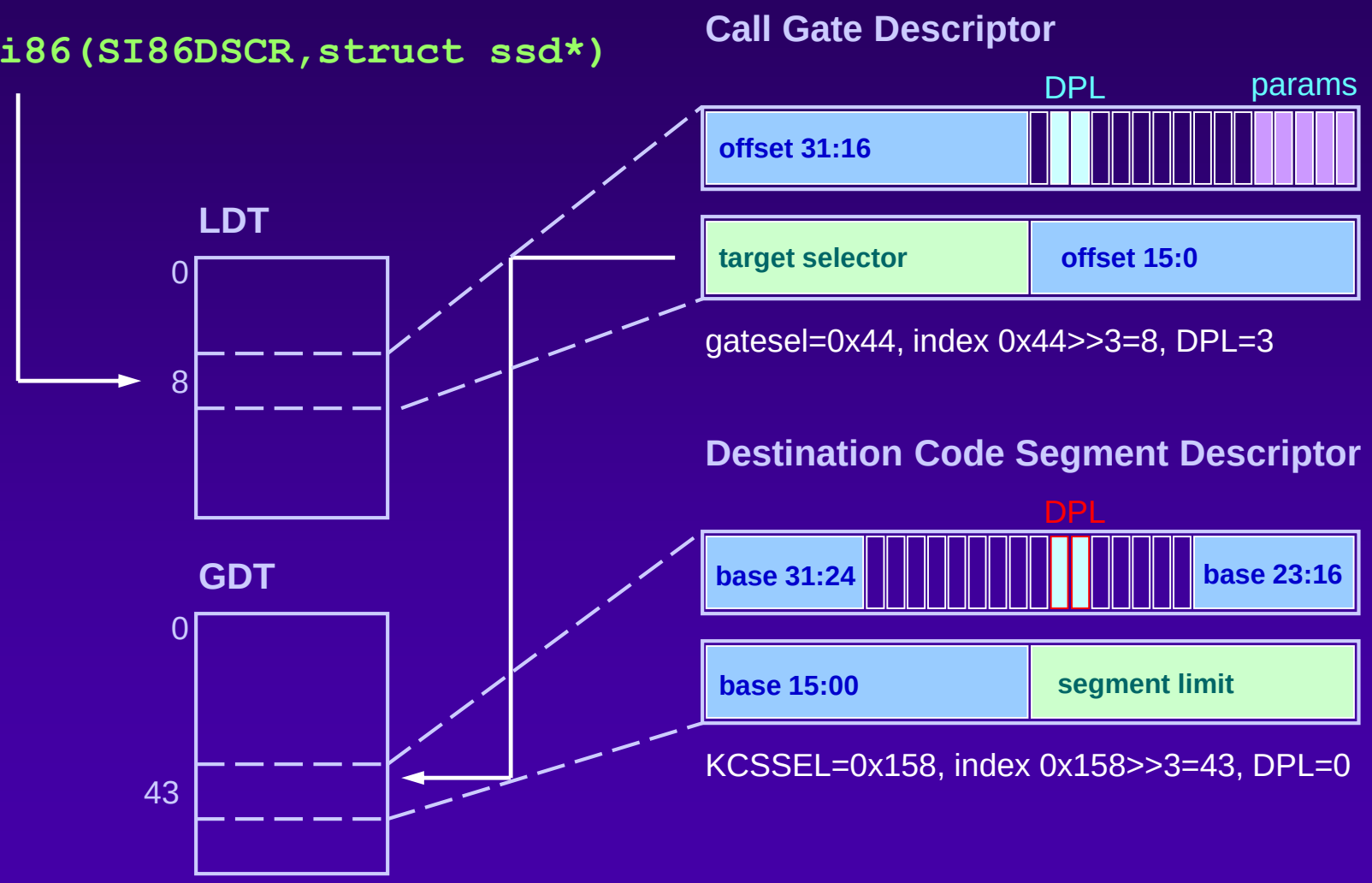
ldt bug - sysi86() system call

DPL of destination segment descriptor is not checked

User program calls:

```
sysi86(SI86DSCR,struct ssd*)
```



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Jumping to the kernel space

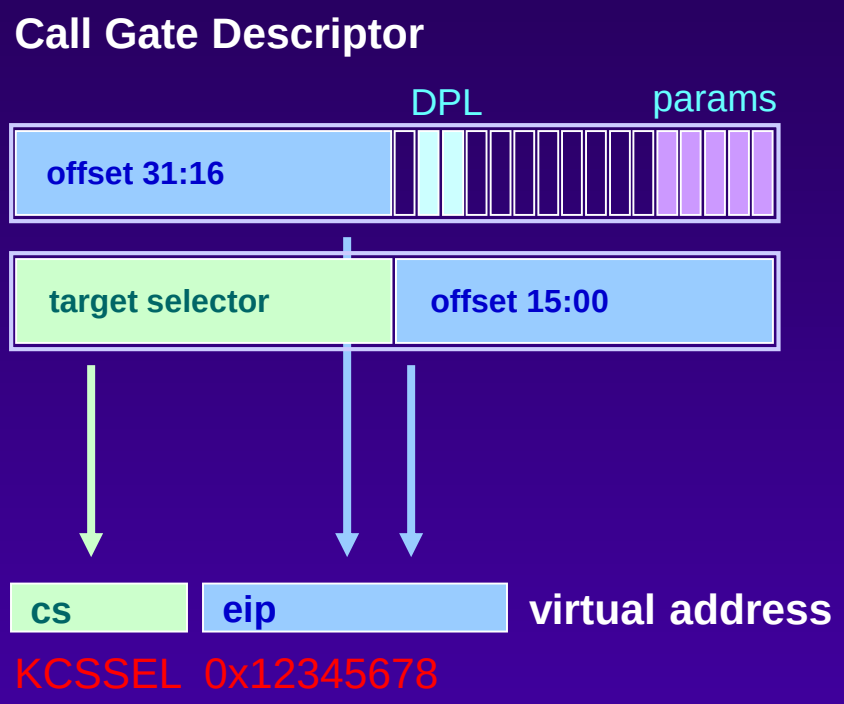
Installation of a call gate

```
s.bo=0x12345678;
s.sel=0x44;
s.ls=KCSSEL;
s.acc1=GATE_UACC|GATE_386CALL;
s.acc2=8;

sysi86(SI86DSCR,&s);
```

Call through the gate

```
lcall    $0x44,$0x00000000
```



Processor tries to execute instruction at new virtual address on most privileged protection level - **panic!**

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Executing code on the kernel stack

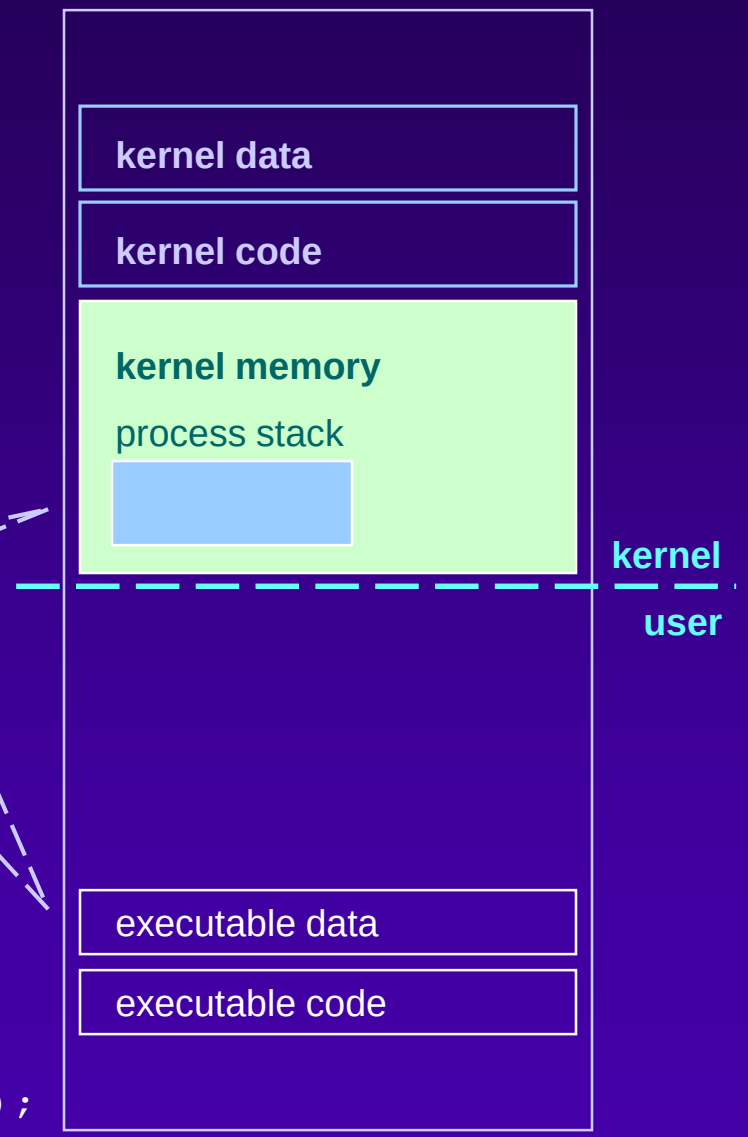
Portion of asmcode[ ] executed on level 3

```
pushl   %ebp
movl    %esp,%ebp
call    <asmcode+8>
popl    %esp
addl    $0x0d,%esp
lcall   $0x44,$0x00000000

leave
ret
```

and level 0

```
nop
nop
lret    $0x20
```



Calculating the destination code address

```
getcontext(&uc);
adr=uc.uc_mcontext.gregs[ESP]+12+4+4-(8<<2);
```

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Executing code in user space

Portion of asmcode[ ] executed on level 3

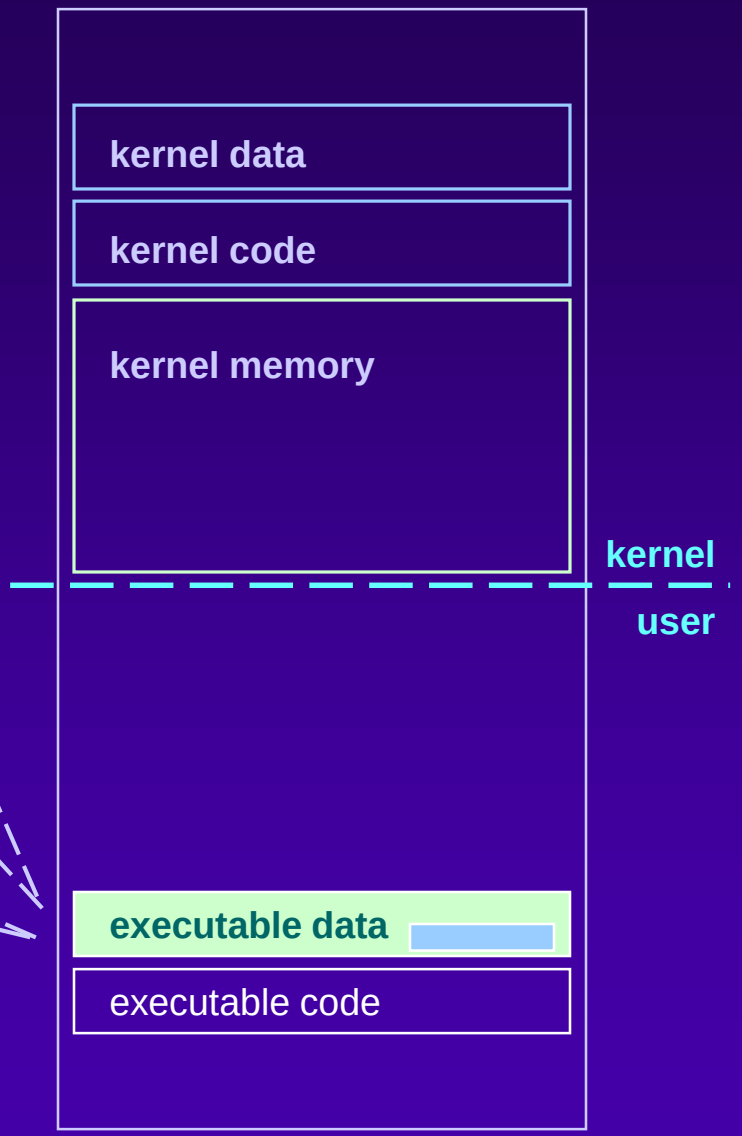
```
pushl   %ebp
movl    %esp,%ebp
call    <asmcode+8>
popl    %esp
addl    $0x0d,%esp
lcall   $0x44,$0x00000000

leave
ret
```

and level 0

```
nop
nop
lret    $0x20
```

Destination code address is known

```
adr=&asmcode[21]
```



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What can be done from the kernel level ?

There are a lot of possible actions that can be undertaken at the kernel level code:

- crash the system
- enable/disable Solaris or Pitbull security settings
- obtain raw access to disk devices
- leverage process credentials
- and more ...

At this point there are actually no active security protections left...

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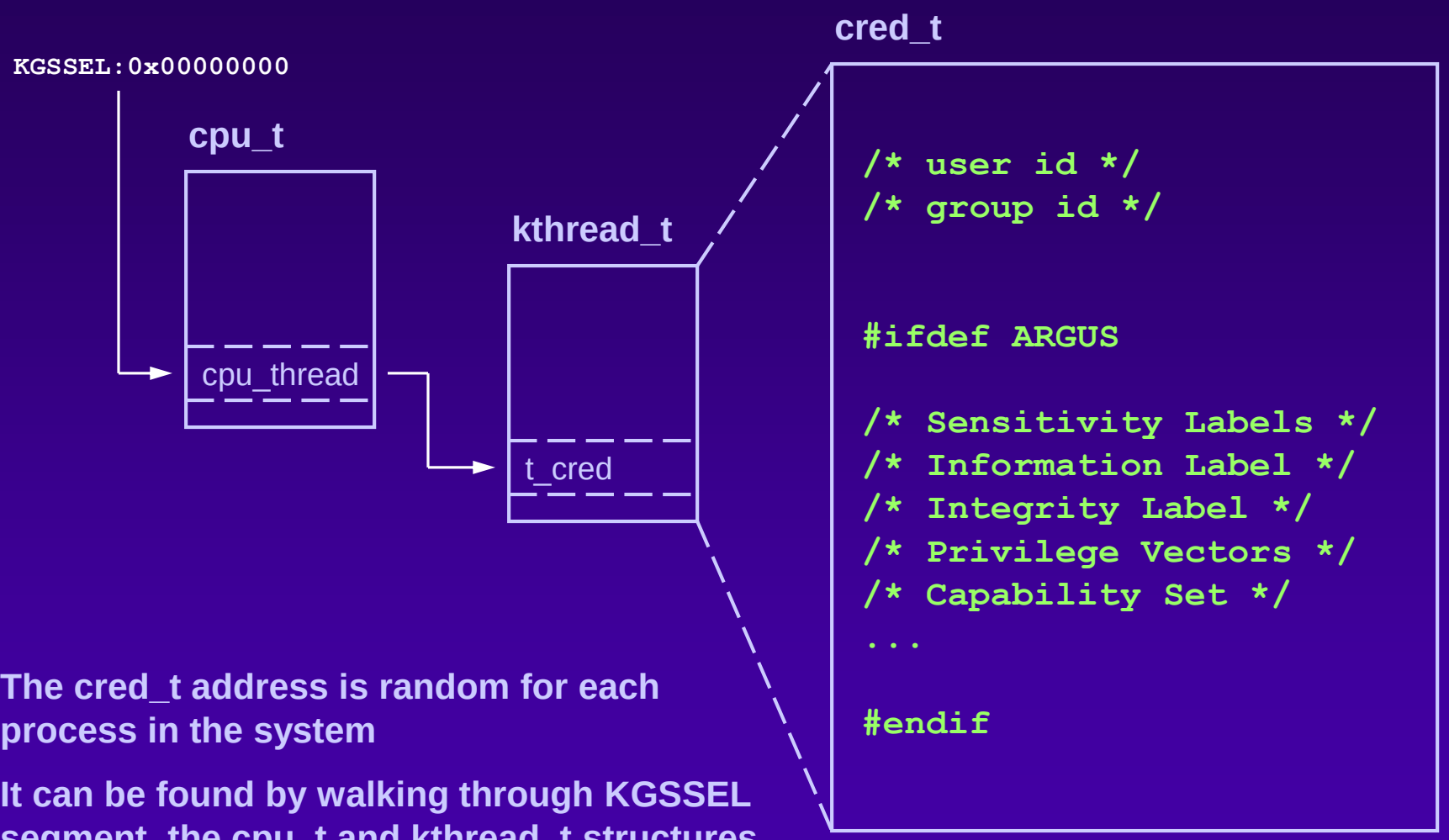
Finding process' cred_t on kernel heap



The cred_t address is random for each process in the system

It can be found by walking through KGSSEL segment, the cpu_t and kthread_t structures

```
ttoproc(curthread)-> p_cred
```

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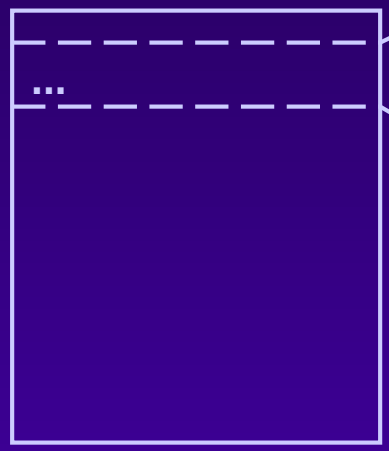
Modification: process user ID

cred_t



Standard UNIX user/group identifiers

```
uid_t cr_uid   /* effective user id */
gid_t cr_gid   /* effective group id */
uid_t cr_ruid  /* real user id */
gid_t cr_rgid  /* real group id */
uid_t cr_suid  /* "saved" user id */
gid_t cr_sgid  /* "saved" group id */
```

Solaris has support for credential management and sharing

- it is better to create copy of cred_t before changing it
- cr_ruid cannot be directly modified as it will result in credential index inconsistency (will crash the system)
- cr_uid is changed

```
setuid(getuid())

p_cred-> cr_uid
```

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Modification: Pitbull sensitivity labels

cred_t

sl_t cr_sl

sl_t cr_cl_min

sl_t cr_cl_max

sl_t

```
#define SC_32 32

typedef struct _sl_t{
    short sl_format;
    short sl_class;
    uint32_t pad;
    union{
        uint32_t un_sl_comp[SC_32];
        long align;
    }sl_comp_un;
}sl_t;
```

To take control over MAC sl_class and sl_comp changes are needed

- changing classification requires setting one single integer value (sl_class)
- assignment to different compartments requires appropriate bits setting in sl_comp[ ] table
- correct ALL value must be selected according the system configuration

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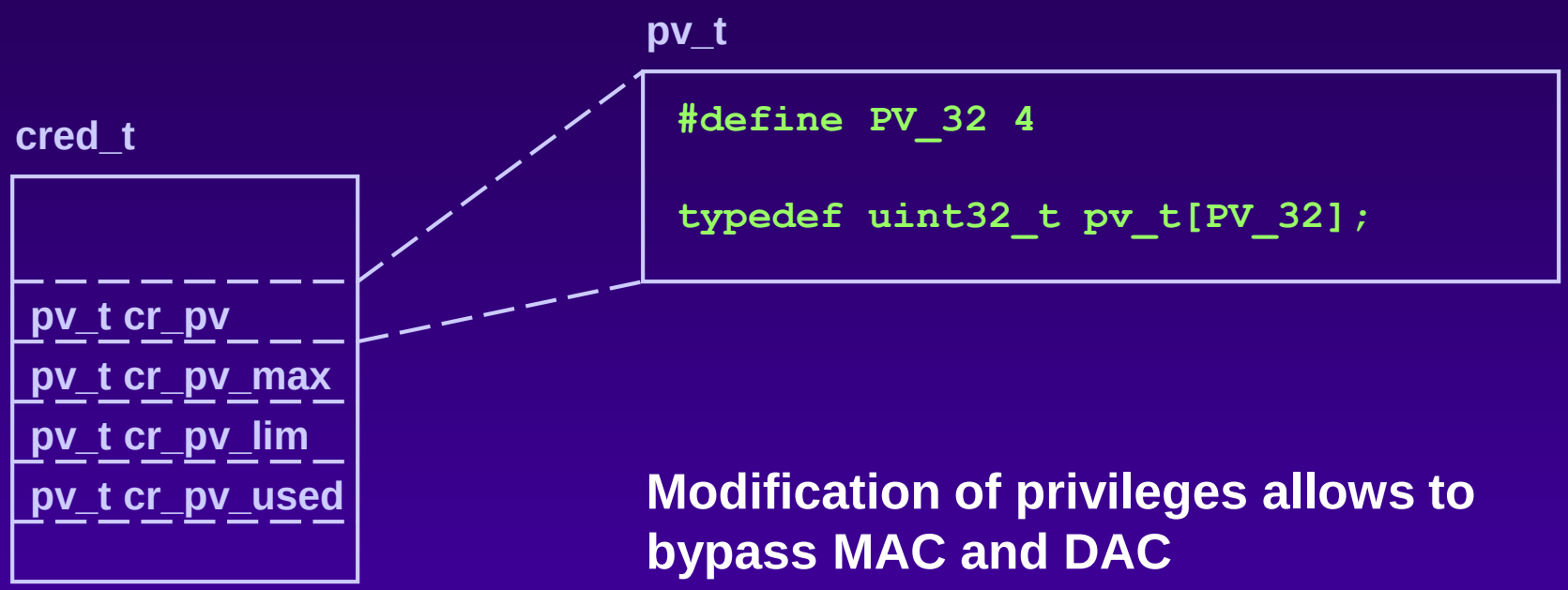
Modification: Pitbull privileges



Modification of privileges allows to bypass MAC and DAC

- in order to grant process all privileges, all bits in pv_t[ ] table must be set to 1,
- after exec() the Pitbull revokes all privileges for the security reasons,
- (sic!) the only exceptions are PV_ROOT* privileges, which are the most powerful and are inherited

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SCO OpenServer setcontext() vulnerability

- Specific to x86 architecture and OS protection mechanisms provided by x86 family of processors
- A kernel level vulnerability, of which impact is very similar to the ldt bug
- Proper exploitation will result in a code execution at 0 protection level of a processor
- The setcontext() system call erroneously allows to set the CS code segment register of a given process to a user supplied value

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The Conclusions

- The case study presented today is a good example of complexity of modern protection as well as attack techniques
- Existence of ldt kernel level vulnerability allowed to bypass security of Solaris system enhanced with Pitbull Foundation, which received various certifications (ITSec B1)
- This proves that there is no such thing like completely secured system
- The other thing is the range of practical impact that kernel level vulnerabilities might have

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The Conclusions (LSD gains and losses)

+ Interesting experience, possibility of participation in great event,
+ An opportunity to meet interesting people,
+ Obviously the prize money (partly paid up to this day),
+ For Michael it was unforgettable bachelor party.

- Long sleepless night,
- 16 liters of Pepsi drunk by 4 persons within 24 hours may influence our health,
- An opportunity to meet interesting journalists.

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Thank you for your attention

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