TRESOR Runs Encryption Securely Outside RAM

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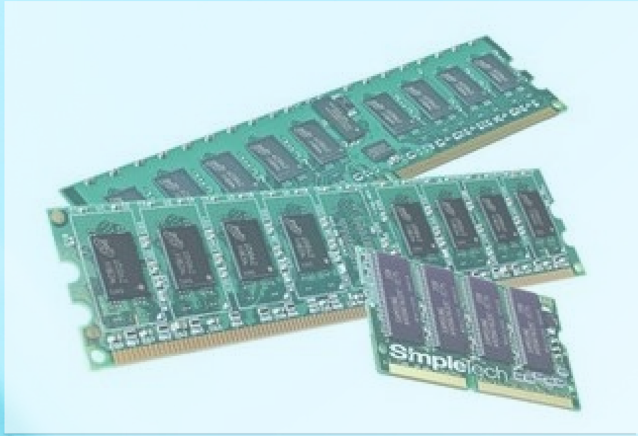
PART I

Introduction



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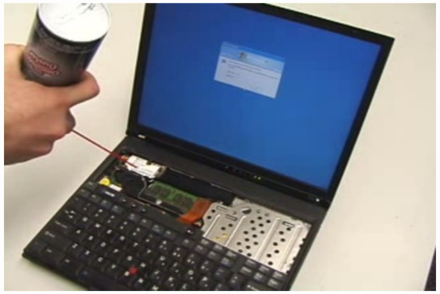
Motivation



Cold Boot Attacks

Firewire Attacks

Other DMA Attacks
- PCI
- PC-Card
- Thunderbolt?

→ RAM is insecure
→ Disk encryption which stores the key in RAM is insecure
Affected: BitLocker, FileVault, dm-crypt, TrueCrypt and more

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TRESOR's Security Policy

TRESOR Runs Encryption Securely Outside RAM:

- AES implementation *solely on the microprocessor*
- Secret keys and states *never* enter RAM
- Instead, only *processor registers* are used as storage

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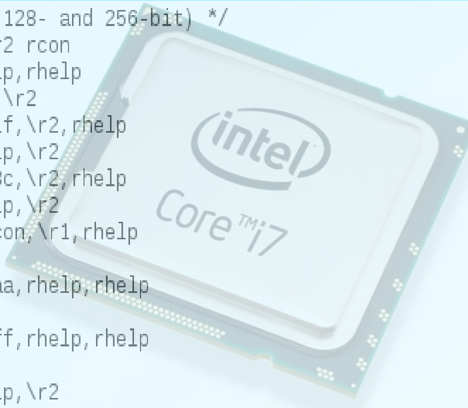
PART II

Implementation

```
+/* generate next round key (128- and 256-bit) */
+.macro  key_schedule r0 r1 r2 rcon
+        pxor            rhelp,rhelp
+        movdqu          \r0,\r2
+        shufps          $0x1f,\r2,rhelp
+        pxor            rhelp,\r2
+        shufps          $0x8c,\r2,rhelp
+        pxor            rhelp,\r2
+        aeskeygenassist $\rcon,\r1,rhelp
+        .if (\rcon == 0)
+        shufps          $0xaa,rhelp,rhelp
+        .else
+        shufps          $0xff,rhelp,rhelp
+        .endif
+        pxor            rhelp,\r2
+.endm
```



Key management: key storage

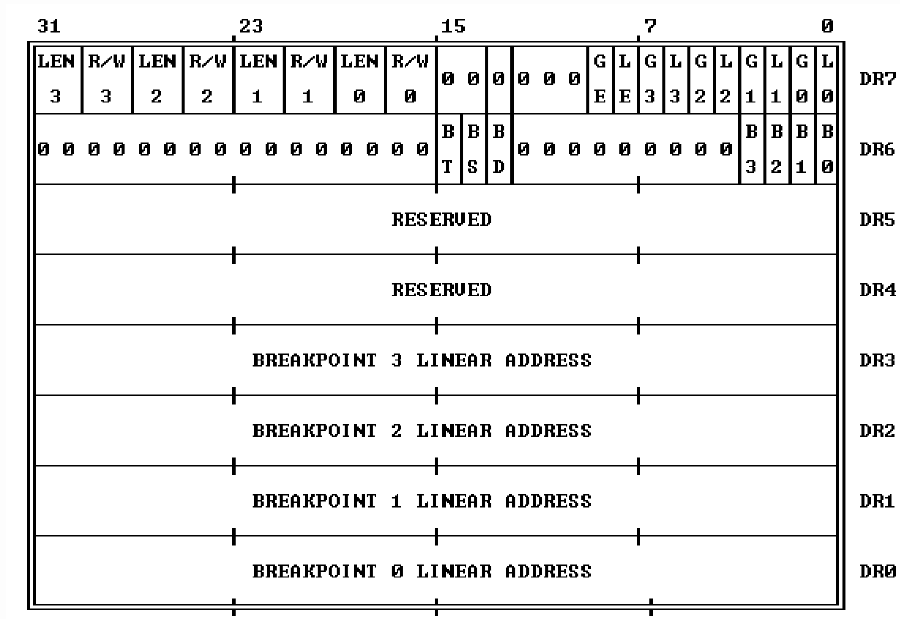
The key registers must be:

- big enough to store AES-128/192/256 keys (*size*)
- a privileged ring-0 resource *(security)*
- seldom used by applications and compensable in software (*compatibility*)

→ fulfilled by the set of *debug registers*

Key management: debug regs

TRESOR (mis)uses debug registers as persistent key storage



→ supports AES-128/192/256 on 64-bit machines
supports AES-128 on 32-bit machines

Key management: key derivation

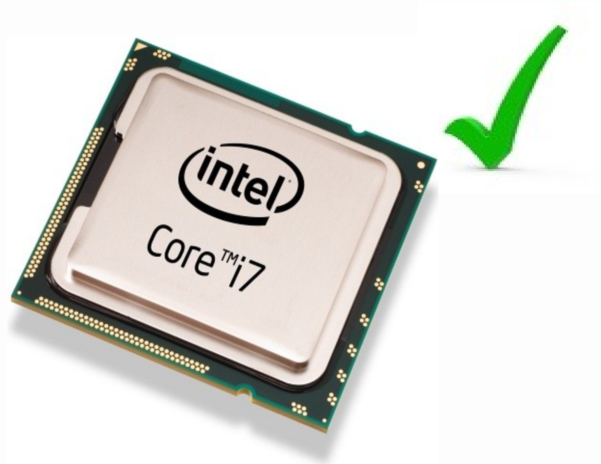
```
>> TRESOR <<

Enter password          > *************

Confirm key hash        > 71 47 15 e1 00 db 94 38 1a 38 fb 91 6f 2a ca 6e
                          42 ec 90 14 a0 9d fc 5c b8 b5 63 9b 4b c2 35 5e

Correct (yes/no)        > yes
```

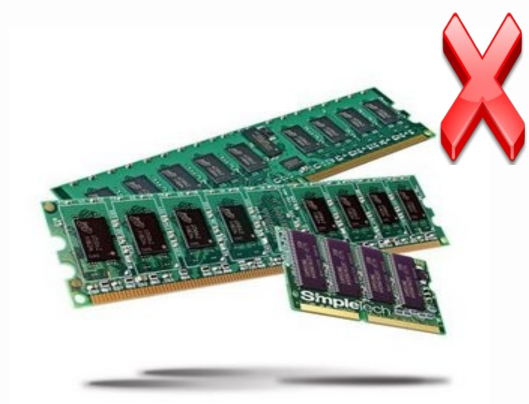
AES Algorithm: guideline

Security Policy: *No valuable information about the AES key or state should be visible in RAM at any time*

Challenge: Implement AES without using RAM at all

→ no runtime variables in data segment (stack, heap, …)
→ use SSE registers and GPRs to store intermediate states
→ written in assembly language (x86)





AES Algorithm: assembly implementation

1. Generic x86 assembler instructions
→ possible, but far too slow

2. Intel's new AES instruction set (AES-NI)
   - hardware accelerated AES instructions
     `aesenc, aesenclast, aesdec, aesdeclast`
   - runs without RAM (instead: SSE)
   - short and efficient AES code

→ does perfectly meet our needs

```
/* Encrypt */
.macro  encrypt_block rounds
        movdqu          0(%rsi),rstate
        read_key        rk0 rk1 \rounds
        pxor            rk0,rstate
        generate_rks_\rounds
        aesenc  rk1,rstate
        aesenc  rk2,rstate
        aesenc  rk3,rstate
        aesenc  rk4,rstate
        aesenc  rk5,rstate
        aesenc  rk6,rstate
        aesenc  rk7,rstate
        aesenc  rk8,rstate
        aesenc  rk9,rstate
        .if (\rounds > 10)
        aesenc  rk10,rstate
        aesenc  rk11,rstate
        .endif
        .if (\rounds > 12)
        aesenc  rk12,rstate
        aesenc  rk13,rstate
        .endif
        aesenclast      rk\rounds,rstate
        epilog
.endm
```

```
/* Decrypt */
.macro  decrypt_block rounds
        movdqu          0(%rsi),rstate
        read_key        rk0 rk1 \rounds
        generate_rks_\rounds
        pxor            rk\rounds,rstate
        .if (\rounds > 12)
        read_key        rk0,rk1,10
        aesdec_         rk13,rstate
        aesdec_         rk12,rstate
        .endif
        .if (\rounds > 10)
        aesdec_         rk11,rstate
        aesdec_         rk10,rstate
        .endif
        aesdec_         rk9,rstate
        aesdec_         rk8,rstate
        aesdec_         rk7,rstate
        aesdec_         rk6,rstate
        aesdec_         rk5,rstate
        aesdec_         rk4,rstate
        aesdec_         rk3,rstate
        aesdec_         rk2,rstate
        aesdec_         rk1,rstate
        aesdeclast      rk0,rstate
        epilog
.endm
```

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AES Algorithm: key schedule

Conventional AES:

round keys are calculated *once* and then stored in RAM
(for performance reasons)

TRESOR:

on-the-fly round key generation
(since the entire key schedule is too big to be stored inside CPU)

```
/* generate next round key  */
.macro  key_schedule r0 r1 r2 rcon
    pxor          rhelp,rhelp
    movdqu          \r0,\r2
    shufps         $0x1f,\r2,rhelp
    pxor          rhelp,\r2
    shufps         $0x8c,\r2,rhelp
    pxor          rhelp,\r2
    aeskeygenassist $\rcon,\r1,rhelp
    .if (\rcon == 0)
      shufps       $0xaa,rhelp,rhelp
    .else
      shufps       $0xff,rhelp,rhelp
    .endif
    pxor          rhelp,\r2
.endm
```

```
/* generate round keys rk1 to rk10 */
.macro generate_rks_10
    key_schedule        rk0  rk0  rk1  0x1
    key_schedule        rk1  rk1  rk2  0x2
    key_schedule        rk2  rk2  rk3  0x4
    key_schedule        rk3  rk3  rk4  0x8
    key_schedule        rk4  rk4  rk5  0x10
    key_schedule        rk5  rk5  rk6  0x20
    key_schedule        rk6  rk6  rk7  0x40
    key_schedule        rk7  rk7  rk8  0x80
    key_schedule        rk8  rk8  rk9  0x1b
    key_schedule        rk9  rk9  rk10 0x36
.endm
```

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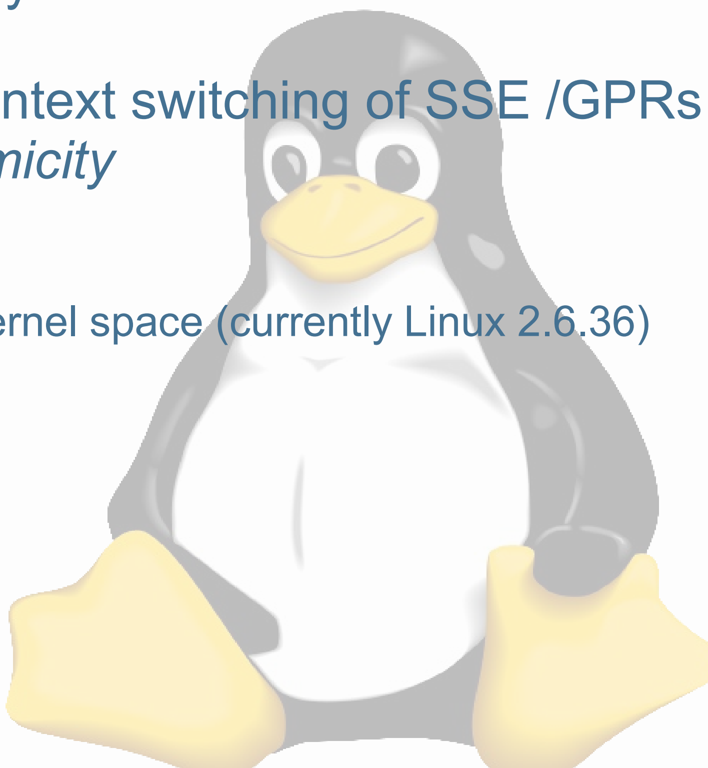
Kernel Patch

We have to *patch the operating system kernel* for two reasons:

1. Problem: unprivileged user access to debug registers
   → Solution: *patch ptrace* syscall

2. Problem: scheduling and context switching of SSE /GPRs
   → Solution: introduce *atomicity*

Hence, TRESOR is implemented in kernel space (currently Linux 2.6.36)



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Kernel Patch: key protection

Risks:

1. Malicious user access to debug registers
   → *compromised key*
2. Writing to debug registers accidentally (e.g., starting gdb)
   → polluting key storage
   → *data corruption*

Solution:

deny access to debug registers from userland

```
int ptrace_set_debugreg (tsk_struct *t,int n,long v)
{
    thread_struct *thread = &(t->thread);
    int rc = 0;
    if (n == 4 || n == 5)
    return -EIO;
  + #ifdef CONFIG_CRYPTO_TRESOR
  +     else if (n == 6 || n == 7)
  +         return -EPERM;
  +     else
  +         return -EBUSY;
  + #endif
    if (n == 6) {
       thread->debugreg6 = v;
       goto ret_path;
     }
    if (n < HBP_NUM) {
       rc=ptrace_set_breakpoint_addr(t,n,v);
       if (rc) return rc;
    }
    [...]
    ret_path: return rc;
}
```

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Kernel Patch: atomicity

- OS regularly performs CPU context switches
- when TRESOR is active this *context comprises sensitive data* (general purpose and SSE registers)

⇒ *run TRESOR atomically*
(per 128-bit input block)

```
/* Encrypt one TRESOR block */
void tresor_encrypt(struct crypto_tfm *tfm, u8 *dst, const u8 *src)
{
	struct crypto_aes_ctx *ctx = crypto_tfm_ctx(tfm);
	unsigned long irq_flags;

	// enter atomicity
	preempt_disable();
	local_irq_save(*irq_flags);

	// encrypt block
	switch(ctx->key_length) {
		case AES_KEYSIZE_128: tresor_encblk_128(dst,src); break;
		case AES_KEYSIZE_192: tresor_encblk_192(dst,src); break;
		case AES_KEYSIZE_256: tresor_encblk_256(dst,src); break;
	}

	// leave atomicity
	local_irq_restore(*irq_flags);
	preempt_enable();
}
```

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PART III

Security Evaluation

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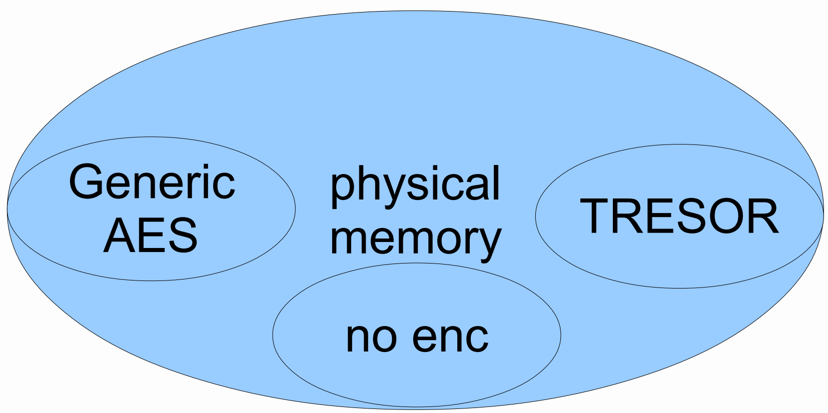
Security Analysis: memory attacks

TRESOR: nothing but the output block is written *actively* to RAM

But: sensitive data may be copied into RAM *passively* by OS side effects
(e.g., interrupt handling, scheduling, swapping, ACPI suspend, etc.)

→ *observe RAM of a TRESOR system at runtime*

Test-Setup:
- KVM/Qemu
- guest1: unpatched Linux, no encryption
- guest2: unpatched Linux, generic AES encryption
- guest3: patched Linux, TRESOR encryption
- examine guests main memories from the host



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Security Analysis: memory attacks

Test 1: Browse guest's main memory with *AESKeyFind*.

Result:

- guest 1 (no enc): no key recovered
- guest 2 (generic AES): key recovered
- guest 3 (TRESOR): no key recovered

But:

AESKeyFind is heavily based on the AES key schedule.
Since TRESOR does not store a key schedule, this may be the only reason why the key cannot be recovered.

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Security Analysis: memory attacks

Test 2: Unlike real attackers we are aware of the secret key.
→ we don't need the key schedule but can search for the key bit pattern directly.

Result:

- guest 1 (no enc): -/-
- guest 2 (generic AES): match found
- guest 3 (TRESOR): no match found

But:

The key could be stored discontiniously, in another endianess, etc.

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Security Analysis: memory attacks

Test 3: Search for the longest match of the key pattern, its reverse and any part of those, in little and in big endian.

Result:

- guest 1 (no enc): -/-
- guest 2 (generic AES): 32-byte longest match
- guest 3 (TRESOR): 3-byte longest match

But:

The key could enter RAM only seldom, in special situations.

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Security Analysis: memory attacks

Test 4: Search for the longest match of the key pattern during ACPI suspend and during swapping.

Result (suspend-to-RAM):

- guest 2 (generic AES): 32-byte longest match
- guest 3 (TRESOR): 3-byte longest match

Result (swapping):

- guest 2 (generic AES): 3-byte longest match on disk
- guest 3 (TRESOR): 3-byte longest match on disk

But:

These are only the most important special states of the Linux kernel. Unfortunately, it is practically impossible to put the Linux kernel into all it's different states and analyze it's memory at the right moment.

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Security Analysis: memory attacks

Test Summary:

AES variant:	Generic AES	TRESOR			None
Kernel state:	normal	normal	swapping	suspend	normal
AESKeyFind	yes	no	no	no	no
Exact key match	yes	no	no	no	-/-
Longest match	32 bytes	3 bytes	3 bytes	3 bytes	-/-

→ we never found sensitive information in RAM or on disk

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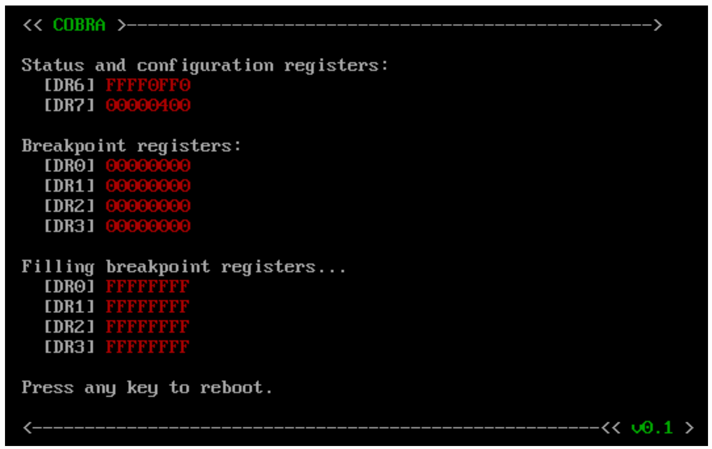
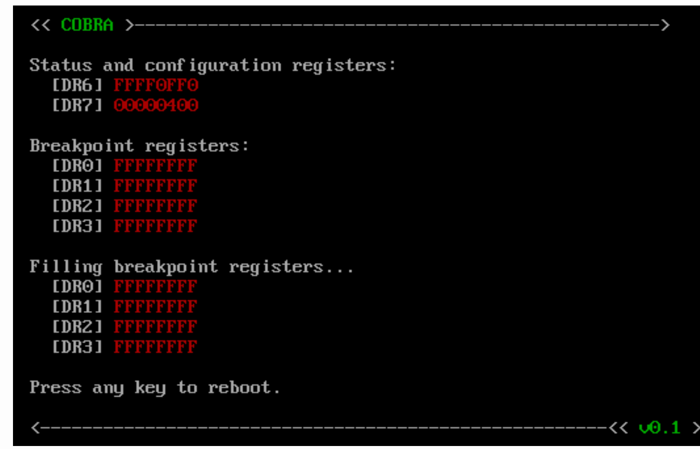
Security Analysis: processor attacks

Cold Boot Register Attack





- Virtual Machines (tested on Qemu, Boch, Vmware and VirtualBox)
  vulnerable
- Real Hardware (tested on seven different CPUs and BIOS versions)
  not vulnerable

Security Analysis: processor attacks

Compromise system space

```
insmod picklock.ko ; dmesg | tail -n 28
[240512.336708] =======================
[240512.336711] DEBUG REGISTERS:
[240512.336841]
[240512.336843] CPU 0
[240512.336846] db0: 0xc7084b3286a3c6eb
[240512.336850] db1: 0xe33d5a7a5db2aa66
[240512.336853] db2: 0xc4e27ee4fea598e2
[240512.336856] db3: 0xff10831b4cbca50b
[240512.337172]
[240512.337173] CPU 1
[240512.337176] db0: 0xc7084b3286a3c6eb
[240512.337179] db1: 0xe33d5a7a5db2aa66
[240512.337181] db2: 0xc4e27ee4fea598e2
[240512.337184] db3: 0xff10831b4cbca50b
[240512.337249]
```

Always possible with superuser rights if
- LKMs are supported
- or /dev/kmem can be written

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PART IV

Future Work

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Current Features

Currently TRESOR supports …

- AES-128 on 32-bit machines
- AES-128/192/256 for 64-bit/AES-NI machines
- multi core/processor environments
- hibernation / suspend-to-RAM
- kernel level encryption: dm-crypt
- Linux kernel 2.6.36

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Future Work

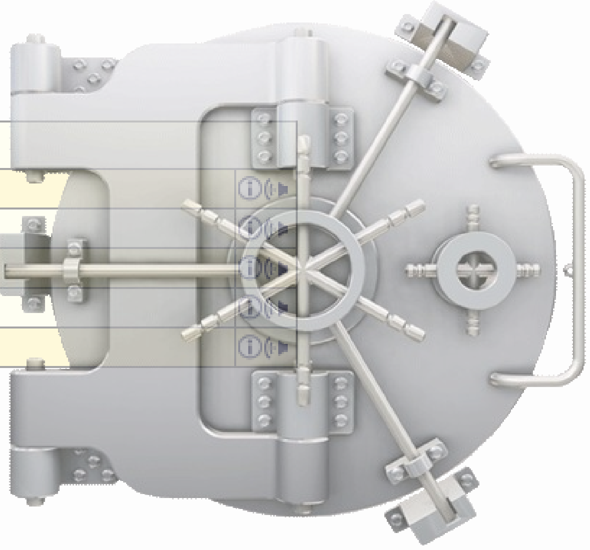
Upcoming releases of TRESOR will support …

- multiple keys and session keys
  (holding a master-key-encrypted keyring in RAM)
- userland encryption
  (via syscalls or, better, via sysfs)
- optionally MSRs instead of debug registers
  (to restore ability of hw breakpoints on a chosen set of CPUs)
- sealing the symmetric key by TPM
  (like BitLocker)
- runtime management
  (enable/disable TRESOR, set new key at runtime, etc.; a bit more insecure but required by server systems with remote-access only)
- Linux kernel 3.0
  (and more long-term stable releases from there on)

TRESOR's name

btw: TRESOR is not just another recursive backronym, it's German for safe / vault ;)

	Substantive (5 of 5)		
	safe		der **Tresor**
	security container		der **Tresor**
	strong room		der **Tresor**
	strongbox		der **Tresor**
	vault [bank.]		der **Tresor**



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Thank you!

Thank you for your attention.

Questions?

E.g., Do you publish the source code?
Of course, it's available under GPLv2 here:
www1.cs.fau.de/tresor

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