Cryptographic Engineering

Cryptographic Engineering — Issues

- Suppose we want to use crypto to protect files. Now what?
- What to encrypt?
- Where should keys be stored?
- What is the tradeoff between availability and confidentiality?

Why Encrypt Files?

- Theft of files
- Theft of backup media
- Theft of computer

Bad Reasons and Good

- Is there a flaw in the operating system's protection mechanisms? Why can't the OS keep bad guys from the file?
- You don't trust the system administrator? Can the sysadmin steal the decryption key?
  ☞But — if you're using NFS, the file may reside on one (untrustworthy) machine, while the decryption is done on another
- Laptops have feet — a remarkably high percentage are stolen

Laptop Theft

September 17, 2000

IRVINE – Qualcomm founder Irwin Jacobs' laptop computer disappeared during a conference yesterday in an apparent theft that could put some of the company's most sensitive secrets at risk.

. . .

Jacobs said his laptop contained "everything," secret corporate information, including e-mail dating back years, financial statements and even personal mementos.

. . .

Though Jacobs' IBM ThinkPad PC is valued at about $3,700, the value of the information it contained is incalculable to Qualcomm and to Jacobs.

Caveats

- Encrypting a file system provides confidentiality
- It generally does not provide integrity protection
- It may result in a *loss* of availability, if you lose the key

Encryption Options

- Manually encrypt/decrypt files
- Overlay encryption on top of the file system
- Encrypt an entire disk partition

Manual Encryption

- Very inconvenient to use
- Users are constantly supplying keys
- Most utilities won't have direct interfaces to the decryption function; you have to manually decrypt files before use
- Users *will* forget to re-encrypt files
- Important design principle: *make it easy for users to do the right thing*

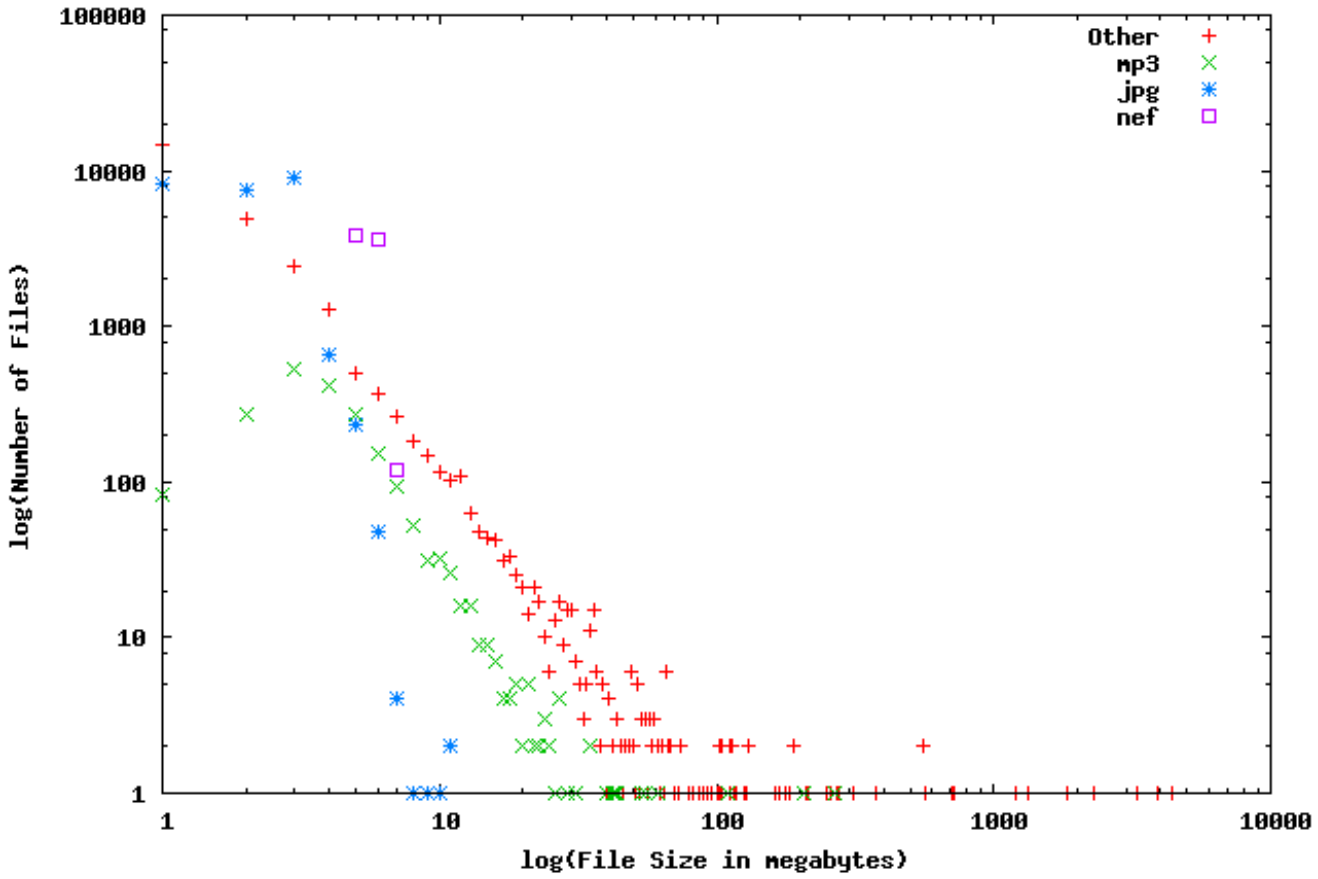
File System Encryption

- Some sort of overlay on real file system
- Encryption and decryption operate on individual files, but transparently to applications
- Directories are files, too, so filenames are encrypted

Problems With File System Encryption

- Metadata is not encrypted
- File lengths are not protected
- File name lengths are not well-protected

File Size Distribution



Population Count For a Few File Sizes

Type	1 MB	2 MB	3 MB	4 MB	5 MB	6 MB	7 MB	8 MB
Other	14839	4832	2413	1280	506	365	265	182
NEF					3891	3649	118	
JPG	83480	7498	8947	648	235	48	4	1
MP3	84	268	532	419	273	150	93	53

Files of 5 MB or 6 MB are — on my disk — very likely to be NEFs; files under 5 MB or over 7 MB are never NEFs. Files of 1–3 MB are probably JPG; files 7 MB and larger are almost never JPG.

Encryption Using CFS

```
$ cattach /usr/mab/secrets matt
Key:
$ ls -ld /crypt/matt
drwx------ 2 mab 512 Apr 1 15:56 matt
$ echo "murder" > /crypt/matt/crimes
$ ls -l /crypt/matt
total 1
-rw-rw-r-- 1 mab 7 Apr 1 15:57 crimes
$ cat /crypt/matt/crimes
murder
$ ls -l /usr/mab/secrets
total 1
-rw-rw-r-- 1 mab 15 Apr 1 15:57 8b06e85b87091124
$ cat -v /usr/mab/secrets/8b06e85b87091124
M-Z,k\x{02C6}]\x{02C6}B\x{02C6}VM-VM-6A\x{02DC}uM-LM-_M-DM-\x
```

Doing the Encryption

- What mode of operation do you use?
  ☞CBC is a good choice
- Where does the IV come from? (Note: on Unix, must support seeks to any byte)
- Partial solution: encrypt each block separately; use block number as part of IV
- Must use some metafile for the rest of the IV. Solution must survive file copies, dump/restore, etc. (CFS uses .pvect files.)
- What about never-written blocks? On Unix, these read as all 0s

Providing Keys for Encrypted File Systems

- File system encryption: can be supplied by user
- Can have fine-granularity keying, per sub-tree
- Disk Encryption: one key per encrypted partition. Shared?
- In either case, once the key is supplied, you rely on OS protection mechanisms
- Bottom line: file system or disk encryption is useful if the threat is compromise from outside the boundaries of the machine: physical theft, remote file system, backup media, etc.
- It is not useful for intra-machine threats; an enemy who can bypass access controls can steal the key or the plaintext
- Encryption is not a substitute for operating system access controls

Disk Encryption

- Encrypt an entire disk or disk partition
- Protects everything, even the free space
- ☞ Very important, given that “delete” operations do not delete the data
- Useful for protecting swap area
- But — free space in encrypted section is not available for plaintext use, and vice-versa
- Problematic for remote file system

Protecting a Key Database

- How does the (symmetric key) trusted party safeguard its database of keys?
- Encrypt it? Where does the decryption key come from?
- One answer: supplied by operator at reboot time
- Another answer: store on a separate file system, so that the key and the encrypted data won't be on the same backup medium
- Tradeoff: availability versus confidentiality and integrity
- Use secure crypto hardware to decrypt database?
- Who has what sort of access, and what are their powers?

How Does a User Store a Key?

- Store key on disk, encrypted
- Generally decrypted with passphrase
- Passphrases are weak, but they're a second layer, on top of OS file access controls

Use Indirection

- Generate a random key to encrypt the data (DEK—Data-Encrypting Key)
- Use the user-supplied key to encrypt the DEK
- ☞ Make changing the password fast
- (Effectively) erase the disk is also very quick

Secure Cryptographic Hardware

- Can be used for users or servers
- More than just key storage; perform actual cryptographic operations
- Enemy has *no* access to secret or private keys
- Friends have no access, either
- Modular exponentiation can be done much faster with dedicated hardware

Hardware Issues

- Hardware must resist physical attack
- Environmental sensors: detect attack and erase keys
- Example: surround with wire mesh of known resistance; break or short circuit is detected
- Example: temperature sensor, to detect attempt to freeze battery

Limitations of Cryptographic Hardware

- Tamper-*resistant*, not tamper-*proof*
- Again: who is your enemy, and what are your enemy's powers?
- (Remember the "crypto in the hands of the enemy" problem.)
- How does Alice talk to it securely? How do you ensure that an enemy doesn't talk to it instead?
- What is Alice's *intent*? How does the crypto box know?
- What if there are bugs in the cryptographic processor software? (IBM's 4758 has a 486 inside. That can run complex programs. . .)

Summary of Key Management and Key Handling

- Sharing cryptographic keys is a delicate business
- Protecting keying material is crucial
- There are no great solutions for general-purpose systems, though proper hardware can prevent compromise (but not misuse) of long-term keys

Random Numbers

- Random numbers are vital for cryptography
- They're used for keys, nonces, primality testing, and more
- Where do they come from?

What is a Random Number?

- Must be *unpredictable*
- Must be drawn from a large-enough space
- Ordinary statistical-grade random numbers are not sufficient
- *Distribution* not an indication of randomness: loaded dice are still random!

Generating Random Numbers

Anyone who considers arithmetical methods of producing random digits is, of course, in a state of sin.

—John von Neumann, 1951

Sources of Random Numbers

- Dedicated hardware random number sources
- Random numbers lying around the system
- Software pseudo-random generator
- Combinations

Hardware Random Number Generators

- Radioactive decay
- Thermal noise
- Oscillator pairs
- Other chaotic processes

Radioactive Decay

- Timing of radioactive decay unpredictable even in theory — it's a quantum process
- Problem: low bit rate from rational quantities of radioactive material
- Problem: not many computers have Geiger counters or radioactive isotopes attached. . .
- See `http://www.fourmilab.ch/hotbits/hardware.html` and `http://www.fourmilab.ch/hotbits/hardware3.html` for a description of how to do it. . .

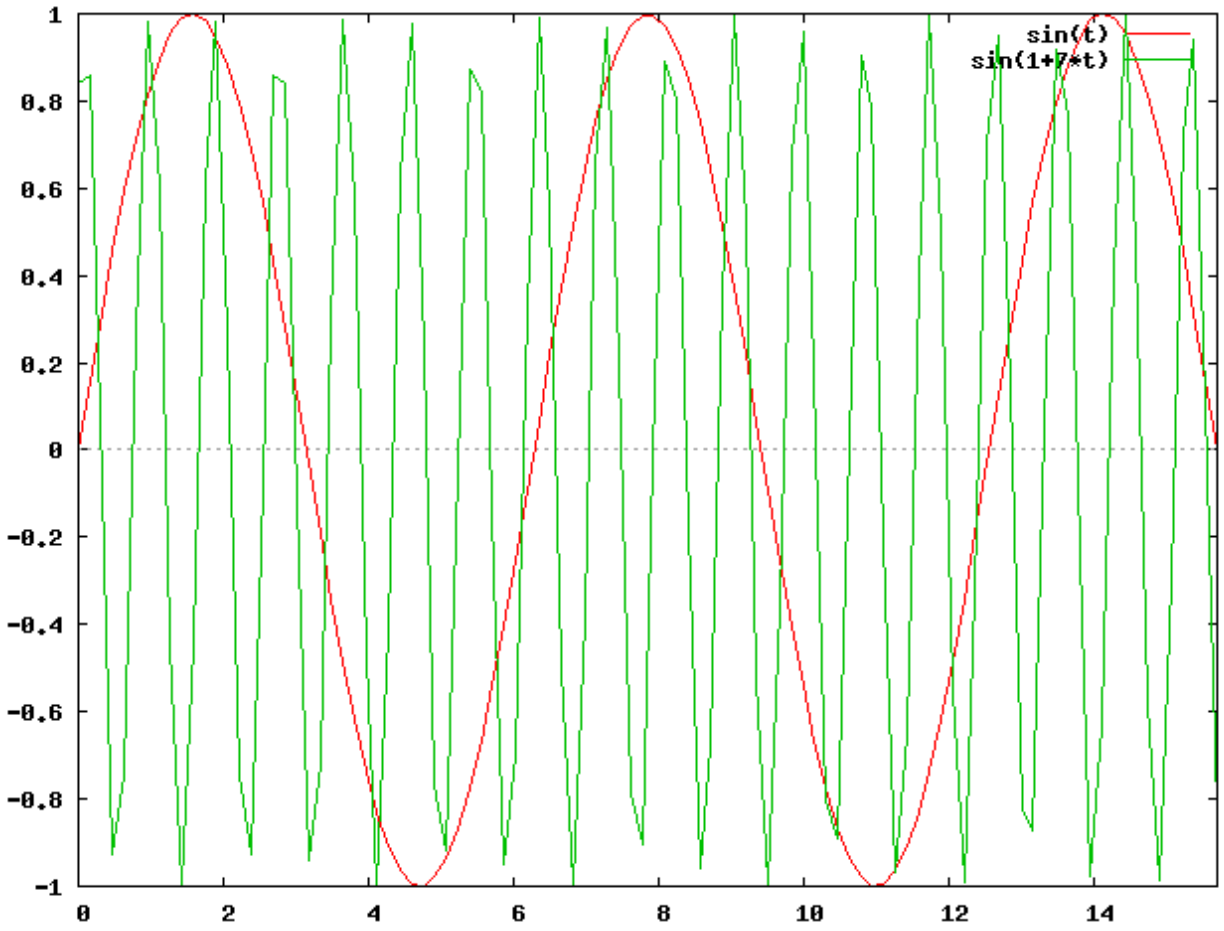
Thermal Noise

- Any electronic device has a certain amount of random noise (thermal noise in the components)
- Example: Take a sound card with no microphone and turn up the gain to maximum
- Or use a digital camera with the lens cap on
- Problem: modest bit rate

Oscillator Pairs

- Have a free-running fast R-C oscillator (don't use a crystal; you don't want it accurate or stable!)
- Have a second, much slower oscillator
- At each maximum of the slow oscillator, sample the value of the fast oscillator
- Caution: watch for correlations or couplings between the two

Dual Oscillator RNG



Other Chaotic Processes

- Mouse movements
- Keystroke timing (low-order bits)
- Network packet timing (low-order bits)
- Disk seek timing: air turbulence affects disk internals (but what about solid state disks?)

☞ At boot time, there's not much of this available

- Also: what if the enemy can observe the process?
- Cameras and Lava Lites®! (`http://www.lavarnd.org/`)

Problems

- Need deep understanding of underlying physical process
- Stuck bits
- Variable bit rate
- How do we measure their randomness?
- *Assurance* — how do we *know* it's working properly?

Software Generators

- Again, ordinary generators, such as C's `random()` function or Java's `Random` class are insufficient
- Can use cryptographic primitives — encryption algorithms or hash functions — instead
- But — where does the seed come from?

Typical Random Number Generator

```
unsigned int
nextrand()
{
        static unsigned int state = 1;

        state = f(state);
        return state;
}
```

What's wrong with this for cryptographic purposes?

Problems

- The seed is predictable
- There are too few possible seeds
- The output is the state variable; if you learn one value, you can predict all subsequent ones

A Better Version

```
unsigned int
nextrand()
{
        static unsigned int state;
        static int first = 1;

        if (first) {first = 0; state = truerand();}
        state = f(state);
        return sha1(state);
}
```

Much Better

- State is initialized from a true-random source
- Can't invert sha1() to find state from return value
- But there is a serious problem here. What is it?

State Space

- sha1() isn't invertible, but we can do a brute force analysis
- `state` is too short, and can can be found in 2^{32} tries
- Estimated resources on a 3.4 Ghz Pentium: 3.6 hours CPU time; 150 GB
- Parallelizes nicely
- Need enough state — and hence enough true-random bits — that brute force is infeasible.

Private State

- An application can keep a file with a few hundred bytes of random numbers
- Generate some true-random bytes, mix with the file, and extract what you need
- Write the file back to disk — read-protected, of course — for next time
- What about stored VMs? Will they get the same seed each time?

OS Facilities

- Many operating systems can provide cryptographic-grade random numbers
- **`/dev/random`**: True random numbers, from hardware sources
- **`/dev/urandom`**: Software random number generator, seeded from hardware
- Windows has analagous facilities

A Well-Known Failure

- As noted, not much randomness is available at boot time
- But—that's often when key pairs are generated
- An RSA public key is the product of two "random" primes
- Might one be predictable?
- Heninger, Durumeric, Wustrow, and Halderman showed that many ssh keys have at least one predictable prime factor, for just this reason

DUAL_EC_DBRG: The NSA Back Door

- NIST decided to standardize a software PRNG

☞ This is a good thing

- NIST picked several designs—and the NSA persuaded NIST to include another based on elliptic curve cryptography
- It seemed odd—DUAL_EC is quite slow, since it's based on public key technology—but the NSA insisted that they needed it. They did need it, but not for the usual reason. . .
- At least one company, RSA, made it the default in their product, allegedly after being paid off

The Problem with DUAL_EC_DBRG

- The algorithm includes a “random” constant
- If it’s not random—if it’s the public key in an elliptic curve cryptosystem—anyone who can see enough of the output from the PRNG *and* knows the corresponding private key can predict all future output from the algorithm
- Many protocols do in fact transmit some random bits in the clear
- There have been public demonstrations that it’s exploitable under certain circumstances
- NIST has removed it from their standard, RSA has removed it from their code. . .

Hardware Versus Software Random Number Generators

- Hardware values can be true-random
- Output rate is rather slow
- Subject to environmental malfunctions, such as 60 Hz noise
- Software, if properly designed and written, is fast and reliable
- Combination of software generator with hardware seed is usually best

Summary

- To paraphrase Knuth, random numbers should not be generated by a random process
- In many systems, hardware and software, random number generation is a very weak link
- Use standard facilities when available; if not, pay attention to RFC 4086