PKI:
Lemon Markets and Lemonade

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Agenda

- **Lemon Markets/PKI Markets**
- **What's the Problem?**
- **Consequences**
- **Solutions**

Lemon Markets / PKI Markets

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Lemon Markets

- Lemon Market: One in which buyers can't distinguish between good-quality and poor-quality goods
  - Won its author George Akerlof the joint Nobel Prize in Economics
- An analogy used to analyze the problem of information asymmetry
  - One side knows more about the product than the other
- Tend to collapse unless a correcting force is applied

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Lemon Markets

- Buyers can't distinguish between good-quality and poor-quality used cars ("lemons"), but sellers can
- Sellers of good-quality used cars can't get a fair price for them
  - Better-quality used cars are withdrawn from the market
  - Buyers revise their expectations downwards
- Sellers of medium-quality used cars can't get a fair price for them
  - Medium-quality used cars are withdrawn …
- Eventually only lemons are left
  - Correcting force: third-party vehicle checks, after-sales warranties, …

Lemon Markets / PKI Markets

- What happens when *neither* side has accurate information about the quality of the product?
  - This leads to a market for silver bullets
  - Insert joke about "a used car salesman knows when he's lying"
- In a lemon market, a failure is obvious
  - If the car you bought breaks down, it's a lemon
- In a silver-bullet market, failures are silent
  - The security is ineffective, but no-one ever notices
    - Any security technology whose effectiveness can't be empirically determined is indistinguishable from blind luck — Geer's Law
  - The security is silently bypassed by attackers, and again no-one notices

What's the Problem?

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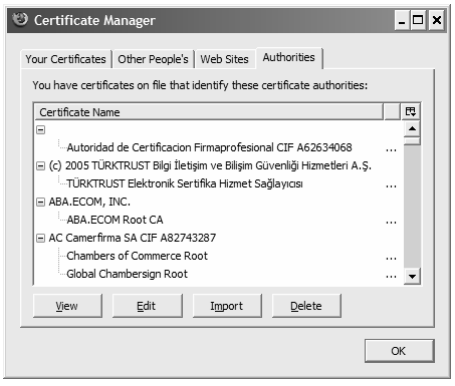
What's the Problem?

- With PKI software, users do have a means of evaluating the product
  - The more capable the software is of accepting any certificate, the "better" it appears to be
- Software that correctly rejects invalid and broken certificates gets dropped in favour of software that blindly accepts anything thrown at it
  - With the amazing invalid certificate, the complaint was that an application was actually rejecting it!
- Acceptance of invalid certificates is a silent failure
  - Rejection of invalid certificates is a very obvious failure of functionality

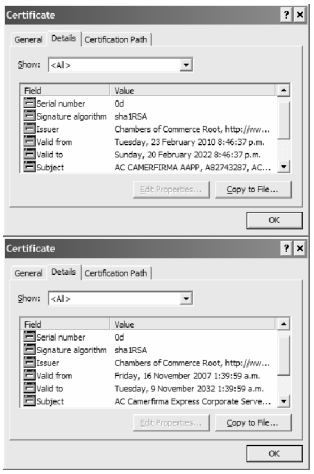
What's the Problem? (ctd)

- In economic terms users are relying not on metrics but on signals
  - A signal is a proxy for information in the absence of a metric that encompasses actually useful information
  - Branding of badge-engineered products is an example of a signaling market
- For PKI software, the deciding metric should be the quality of the implementation, the accuracy with which it rejects invalid certificates
  - (On a more abstract level it's the effectiveness with which it secures transactions/messages, but this is hard to quantify)
- In the absence of this information, users rely on signaling, the ability to accept and process the widest possible range of certificates

What's the Problem? (ctd)



What's the Problem? (ctd)



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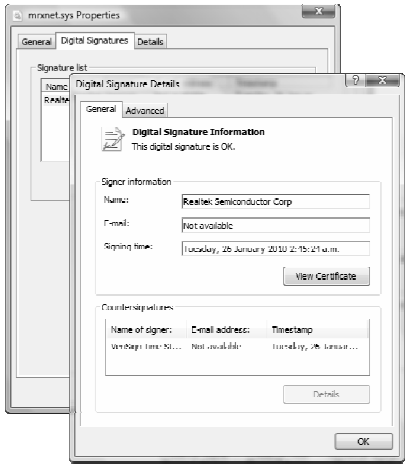

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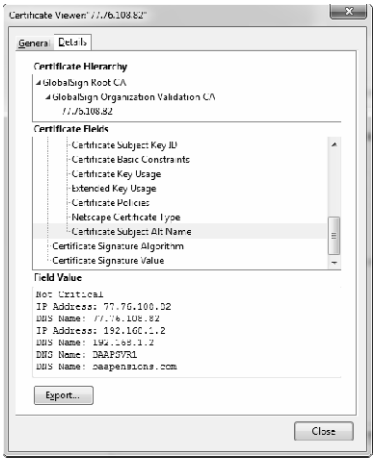
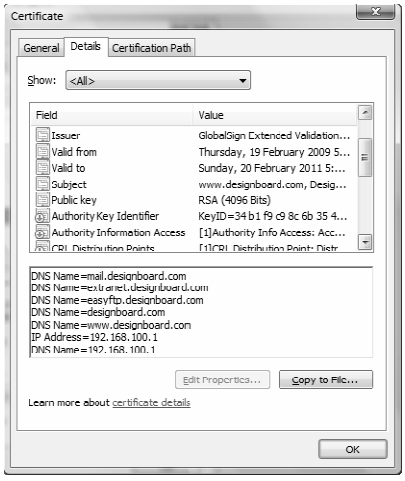
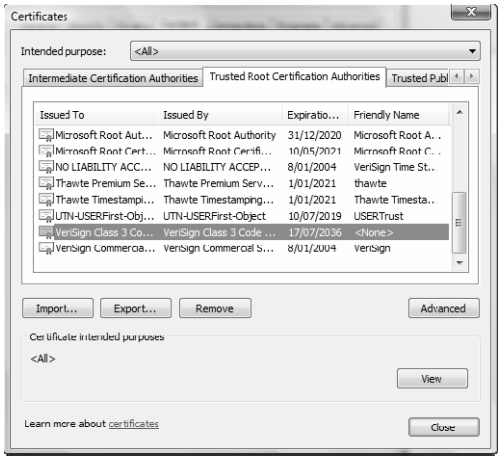


What's the Problem? (ctd)



What's the Problem? (ctd)

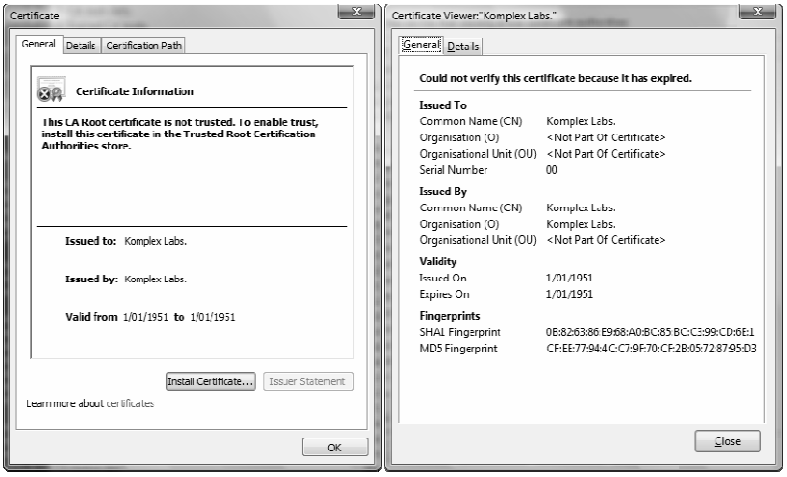


What's the Problem? (ctd)

What's the Problem? (ctd)

```
-----BEGIN CERTIFICATE-----
MIIQojCCCIoCAQAwDQYJKoZIhvcNAQEEBQAwGDEWMBQGA1UEAxMNS29tcGxleCBM
YWJzLjAeFw01MTAxMDEwMDAwMDBaFw01MDEyMzEyMzU5NTlaMBgxFjAUBgNVBAMT
DUtvbXBsZXggTGFicy4wggggMA0GCSqGSIb3DQEBAQUAA4IIDQAwgggIAoIIAQCA
A++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
+////////////////////////////////////////////////////////////////+
+////////////////////////////////////////////////////////////////+
+///++++HELLO+THERE++++////////////////////////////////////////////+
+////////////////////////////////////////////////////////////////+
+///And/welcome/to/the/base64/coded/x509/pem/certificate/of///+
+////////////////////////////////////////////////////////////////+
+///KOMPLEX/MEDIA/LABS//////////////////////////////////////////+
+///www/dot/komplex/dot/org/////////////////////////////////////+
+////////////////////////////////////////////////////////////////+
+///created/by/Markku+Juhani/Saarinen//////////////////////////+
+///22/June/2000///dw3z/at/komplex/dot/org/////////////////////+
+////////////////////////////////////////////////////////////////+
+///You/are/currently/reading/the/public/RSA/modulus/////////////+
+///of/our/root/certification/authority/certificate/////////////+
+////////////////////////////////////////////////////////////////+
+///Which/happens/to/be/16386/bits/long/////////////////////////+
+////////////////////////////////////////////////////////////////+
+///And/fully/working/and/shit//////////////////////////////////+
+////////////////////////////////////////////////////////////////+
+///And/totally/insecure///////////////////////////////////////+
+////////////////////////////////////////////////////////////////+
```

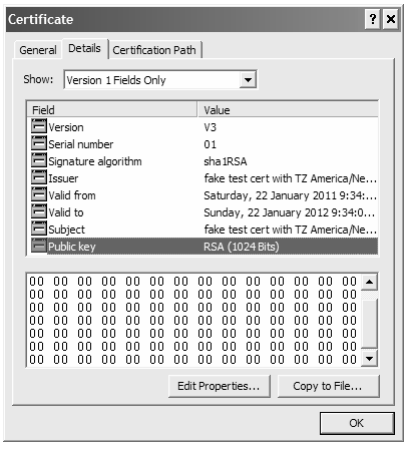

What's the Problem? (ctd)



What's the Problem? (ctd)

- This certificate…
  - Looks a bit suspicious
  - Dates from the 1950s
  - Has a negative validity period
  - Is unsigned (!!)
- Apart from trust-related bookkeeping issues, neither Windows nor Firefox see a problem with this

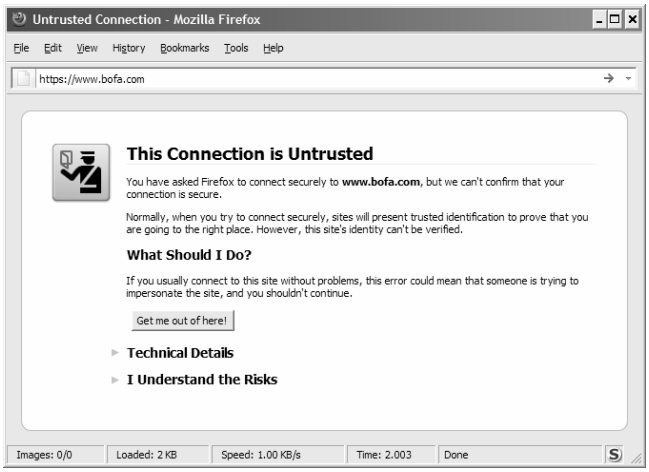
What's the Problem? (ctd)



What's the Problem? (ctd)

- This certificate has…
  - An invalid issuer name
  - An invalid subject name
  - An invalid start date
  - An invalid end date
  - An invalid public key
  - An invalid signature
- It's actually hard to find anything in this certificate that's valid
  - Well there's the serial number…
- It's OK though, Windows and OpenSSL accept it

What's the Problem? (ctd)



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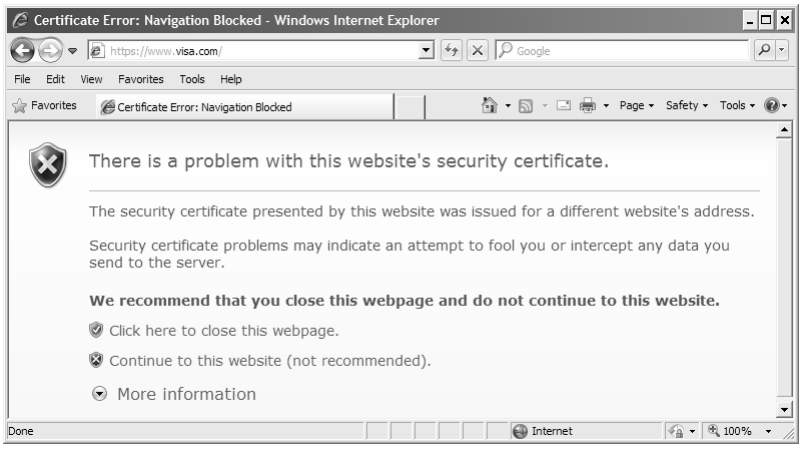

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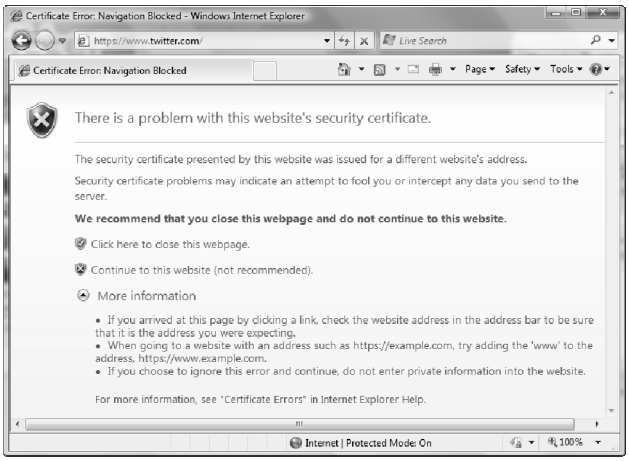

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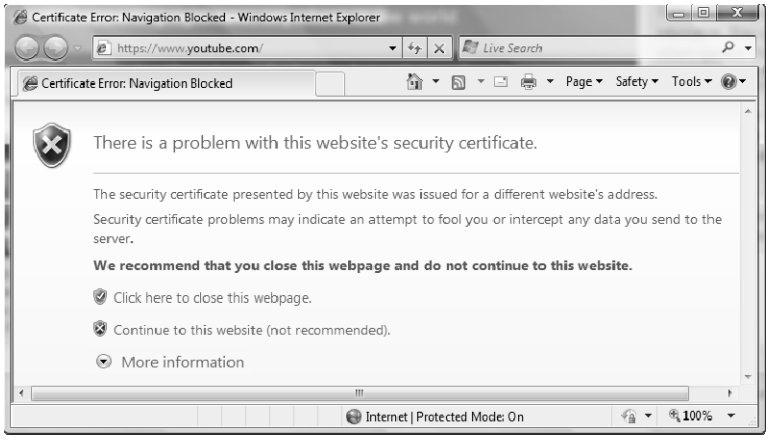

What's the Problem? (ctd)

- Admittedly some of the problems illustrated are more due to-lax-to-nonexistent CA checking
  - Getting screenshots of bugs in software is difficult
- Still, we have a (serious) problem
- There is no economic term for such a situation
  - This is something that can't occur in conventional economics, since it leads to market failure
- Since there isn't a term defined for this, I propose "PKI Market" to match the existing concept of a "Lemon Market"

Consequences

Consequences

- A PKI market produces a toxic codependency of broken certificates and broken code
  - Certificates can be broken because the code doesn't reject them
  - As a result, code can't reject broken certificates because there are too many of them out there, and users would switch to code that doesn't reject them
- Why is this stuff so hard to get right?
  - ACLs/Firewall rules: Allow/disallow based on a pattern-match
  - Certificates: Vast amounts of custom business logic

Consequences (ctd)

- Disabling validity checks in order to make PKI "work" is fairly widespread
  - Two widely-used security toolkits allow user-defined verification callbacks to supplement or replace standard checks
  - Many applications implement this as 'return 1'
  - Practice is institutionalised in manuals and user guides
  - Financial transaction processor "by way of some awful documentation and sample code" tells vendors how to make an SSL connection insecurely
  - stunnel does this by default
  - German national ID card software didn't bother performing any checking, so any certificate was regarded as valid
  - Many, many more examples of PKI apps doing similar things

Discussion Overview

- Problems
  - BasicConstraints/KeyUsage
  - Key Identifiers
  - DNs
  - CRLs
  - PKI Services
- Solutions

Basic Constraints

- basicConstraints.cA flag
  - The single most basic value in a certificate
  - Boolean flag, “is a CA” / “is not a CA”
- Many major platforms simply ignored this until 2002 when bad publicity involving a fake Amazon site “certified” by Verisign forced a fix
  - For the first ~10 years in which some of these technology platforms were deployed, they couldn’t get a basic boolean flag right

Key Usage

- Conformance is more or less arbitrary
  - One often-seen practice is to ignore the flag and use the first certificate you find for any purpose you feel like
- Windows happily uses encryption-only (AT_KEYEXCHANGE) keys for signing…
  - … and signing-only keys for encryption:
  - "the certificates [has the digitalSignature flag set] so the public key can only be used to verify a signature, but in the logon procedure the key is also used to [decrypt]. This is NOT allowed because the [keyEncipherment flag is not set]"
- This was particularly distressing in this case because it voided guarantees provided under European digital signature laws

Key Usage (ctd)

- European PKI vendor ran an interop server for other PKI vendors to test against
  - A who's-who of vendors successfully did
  - After two years someone pointed out that the keyUsage in the server's certificate didn't actually allow this
- Global software vendor ran an interop site for its flagship server product
  - Server authentication key was marked as unusable for server authentication
  - After several years' operation, no-one had noticed

Key Usage (ctd)

- Microsoft NDES SCEP server used to provision Apple iPhones
  - iPhone happily encrypts to a signature-only certificate, ignoring the keyUsage constraint
  - Works OK though because the Microsoft server at the other end ignores it as well
- European CA marked its signature key as not being valid for signatures
  - CA marked a certificate used to encrypt data for a national tax authority as usable only for digital signatures
  - Another CA reversed the order of the flags in keyUsage due to confusion over endianness, effectively setting random flags

Key Usage (ctd)

- keyUsage flags seem to be set arbitrarily by some public CAs
  - Specify keyUsage.keyEncipherment or keyUsage.keyAgreement when the algorithm in the cert isn't capable of doing this
- One CA set DH keyUsage.keyAgreement (for an RSA key)
  - Set keyUsage.encipherOnly
  - Just to be fair, set keyUsage.decipherOnly as well

Key Usage (ctd)

- European PKI project approached this from another angle
  - Marked encryption-only certificates with "ENC" in the DN and signature-only certificates with "SIG"
  - Tested the certificates with PKI software
  - "ENC" certificates worked fine for encryption, "SIG" certificates worked fine for signatures
  - Product was shipped and widely used
  - Quite some time later, a technically-minded user noticed that the software would select and use "ENC" and "SIG" keys more or less at random
    - "ENC" keys had supposedly been kept in escrow
    - Destroyed the validity of the signing process since keys held by a third party had been used for signing

Key Identifiers

- Certificates contain two binary identifier fields, subjectKeyIdentifier (SKID) and authorityKeyIdentifier (AKID)
  - These have very different encodings
- Some CAs memcpy() the SKID to the AKID, creating an invalid encoding
  - When tested against a wide range of PKI software, nothing noticed this
  - Not only were they not paying any attention to the keyIdentifier values, they weren't even trying to decode the extension that held it

Key Identifiers (ctd)

- Variations on this abound…
- European CA encoded the AKID as an empty value
  - Implying the certificate was issued by nobody?
- CAs create circular references
  - AKID points back to itself
  - Presumably an implementation would need to go into an endless loop to process this
- CAs use duplicate SKIDs
  - In one case probably due to it being derived from a time-based value, because batches of certificates issued in close proximity had identical SKIDs
- Adobe's cert handling for signed PDFs does pretty much the exact reverse of what it's supposed to with the KIDs

Key Identifiers (ctd)

- Copy-and-paste PKI
  - Find something that works elsewhere and copy and paste it into your PKI
  - A good idea for regex's, SQL expressions, Perl scripts, …
  - Less good for PKI
- AKIDs point to random unrelated CAs
- SKIDs for all certificates are identical
- authorityInfoAccess points to unrelated CAs
  - Blacklist-based operation in CRLs and OCSP means that such certificates can never be revoked
  - The use of blacklist- rather than whitelist-based checking also means that the failure isn't noticed during normal use

DNs

- If two implementations disagree over what goes where in a DN, they will/won't check different portions of the DN and related fields
- How to abuse DNs/altNames as hiding places
  - Request a certificate with different identifiers placed in locations regarded as being equivalent
    - See earlier screenshots of RFC 1918 certificates
  - CA verifies the identifier in one location
  - PKI software uses a supposedly-equivalent but unverified identifier from another location

DNs

- Examples include Moxie Marlinspike's '\0' DN strings
  - Request a certificate for 'www.microsoft.com\0mydomain.com'
  - CA verifies 'mydomain.com', PKI software uses 'www.microsoft.com\0'
  - At Defcon 2009, a selection of geeks bought certificates for Adobe, Apple, Microsoft, Verisign, Yahoo, and others, until they ran out of money
- As with many other PKI failures, this wasn't fixed until it got media attention due to the creation of a bogus Paypal certificate

DNs (ctd)

- LDAP format represents DNs in reverse order to how they're present a certificates and cert-using protocols
  - Some Java implementations do this too
  - As a result, DNs in certificates can be encoded forwards or backwards
- .NET GetIssuerName and GetSerialNumber return the information in reverse order to the MMC certificate snap-in
  - Different versions of software, e.g. IIS 4 and IIS 5, processed the bytes in opposite order
- This interferes destructively with X.509's blacklist-based checking

DNs (ctd)

- Not only can DNs end up encoded forwards or backwards, they can even be forwards and backwards in the same certificate
  - One European national CA encodes DNs forwards and backwards apparently at random
  - Others are more consistent and get the DN backwards in all certificates
  - Others get the issuer name, via memcpy(), forwards, but the subject name backwards
  - Some certificates contain DN components in more or less arbitrary order
    - This includes duplicate AVA instances in different parts of the DN

Make it a Feature!

- Some European CAs use this to their advantage when the CA is also the PKI vendor
  - CA will only process certificates produced by its own buggy software
  - Software will only accept buggy certificates issued by the CA
- Use of a particular European CA was mandated by government decree
  - Would only issue certificates to users using the CA's broken PKI toolkit
  - The term for this in the country in question is apparently "appointing a goat as gardener"

Make it a Feature! (ctd)

- Another CA quietly dropped requests created by anything other than its own software
  - Use of the CA's services was government-mandated
  - Ensured that only products sold by the CA's consulting arm could be used
- Another CA added incompatible modifications to a standard PKI protocol "for security reasons"
  - The financial security of the CA, that is
  - Had to buy the CA's software to get your request processed

PKI Services

- No better than the basic certificate handling…
- TSA had a soft-failure that caused it to reject any request for a timestamp
  - No-one using the service, which delivers tens of thousands of timestamps a month, noticed that their data wasn't being timestamped any more
- TSA client submitted not a hash of the document to be timestamped but the entire document
  - Server took the first 20 bytes and timestamped that
  - Used with European high-assurance (qualified) signatures

Summary

- After twenty years, we've almost got to the point where we can rely on the most basic extension in a certificate, basicConstraints.cA
  - Even the next most basic one, keyUsage, is handled more or less arbitrarily
  - Beyond that, it's a crapshoot
- "There's not a single X.509v3 extension defined in PKIX a PKI designer can really rely on. For each and every extension somebody planning/deploying a PKI has to check each and every implementation if and how this implementation interprets this extension. This is WEIRD!"
  — PKI developer Michael Ströder

Summary (ctd)

- There is a complete absence of any kind of quality control in PKI software
  - One large PKI vendor for many years had no documentation whatsoever for their code's functionality
  - Developers were handed the code and told that the software's functionality was defined to be whatever you got when you fed it a certificate
  - One new developer's first task was to reverse-engineering what the code did based on observed behaviour with various certificates
- You can't build something so broken that it can't claim to be X.509…
  - … and vendors frequently do

Solutions

Solutions

- Good news: We have near-infinite scope for improvement!
- There are four ways to deal with this problem…
  - 1. The Ostrich algorithm
  - 2. PKI overlay networks
  - 3. Field-qualify your PKI applications
  - 4. Work defensively

1. The Ostrich Algorithm

- Everything's working fine, nothing to see here, move along
- Popular with PKI created for its own sake
  - Target for the consultants was "You asked for PKI, here is PKI, you didn't specify that it had to work"
- This isn't as bad as it sounds: Attackers seem to be using the Ostrich Algorithm as well
  - Baffled by its complexity?
  - Easier targets elsewhere?
  - Not protecting anything worth attacking?
- (Probably the last one on the list)

2. PKI Overlay Networks

- Layer your own custom security controls on top of the general-purpose PKI
  - Requires at least some control over the PKI software
- Leverages existing investment in PKI software while providing add-on functionality that provides the services/functionality that you need
  - A bit like an overlay network built on top of the Internet

2. PKI Overlay Networks (ctd)

- Done by Microsoft for its code-signing certificates
  - Code-signing certificates need a special code-signing extendedKeyUsage
  - Must be present in CA root certificates to prevent a downstream CA from manufacturing their own code-signing certificates
  - Signatures can be verified after the certificate expires via a countersignature mechanism
  - Assorted other special-case handling, e.g. for boot code that can't rely on a CRL being available
  - Verification code is created and controlled by Microsoft to do what it wants
- Disadvantage: Not everyone is Microsoft

3. Field-qualify Your PKI Apps

- Try to field-qualify every version of every application on every platform that you plan to use
  - This is impossible in general
- It may be effectively impossible even for specific cases…
  - One survey of SSL/TLS server certificates found 219 different combinations of keyUsage and basicConstraints.cA flags, including many that were totally illogical

3. Field-qualify Your PKI Apps

- Tests are extremely tricky and tedious
  - Need to verify that things that should happen, do happen
  - Need to verify that things that shouldn't happen, don't happen
  - This comes close to trying to prove a negative
  - Need to re-run the tests every time an application update occurs
- CRLs and OCSP make this especially tricky
  - A successful verification against a blacklist is indistinguishable from a failed check

3a. Field-qualify Your PKI Apps (ctd)

- Variant: Require the use of one specific piece of software everywhere
- Possible in closed environments
  - Inside corporates
  - Closed B2B
- Still need to qualify the PKI software, but now the scope of the operation is limited

3b. Field-qualify Your PKI Apps (ctd)

- Variant: Only use the restricted subset of PKI functionality that you can verify works
  - Don't discard it all, since it least some of it works some of the time
- Possible in controlled environments
  - All parties agree in advance on which subset to use
- As before, still need to qualify the PKI software, but again the scope of the operation is limited

4. Work Defensively

- Assume that nothing will quite work as expected and build your system appropriately
  - When building a system from unreliable components, the less of the unreliable components that you have to depend on, the smaller the chances of an unpleasant surprise later on
- There's nothing to say that you have to use certificates as anything more than a complex bit-bagging mechanism

4. Work Defensively (ctd)

- Example: Use standard presence checks to replace unreliable PKI mechanisms
  - Certificate present in a database $\Rightarrow$ access allowed / certificate is OK
  - To revoke access, remove the certificate from the database
- Avoids the need for CAs, CRLs, OCSP, bridge PKI, certificate path building, chain verification, …
  - All the dysfunctional portions of PKI are eliminated
- Use of Active Directory to manage certificates for account login is an example of this

4. Work Defensively (ctd)

- Variant: Drop PKI entirely
- Why exactly are you using it?
  - "It seems to be the expected thing to do" isn't a reason
- Seriously, why do you actually need a PKI for what you're doing?
  - Name five alternative options that solve the same problem, and provide reasons why PKI is the better choice

4. Work Defensively (ctd)

- Example: Network authentication
  - TLS-SRP and TSL-PSK solves this problem far better than PKI ever can
  - True failsafe mutual authentication
  - PKI can only provide unilateral authentication in both directions …
  - … and then you have to deploy, manage, and run a PKI to get there
- Example: Secure email between corporate offices
  - STARTTLS solves this problem far better than S/MIME can
  - S/MIME: … and then you have to deploy a PKI …
- Do you really want to hold your business hostage to PKI?

Apply Slide

- Assume that a certificate may be little more than a complex bit-bagging scheme
- Treat certificates as a simple signed access token
- No need for external CAs, PKI heirarchies, OCSP servers, or other complex and expensive PKI folderol
- Presence in a database ⇒ certificate is OK
- Access control is handled by removing the certificate from the database, not hoping that a CRL or other check works
- Do you really need a PKI for what you're trying to do?

Further Reading

- Detailed writeup, background material, and references to sources can be found in
- http://www.cs.auckland.ac.nz/~pgut001/pubs/book.pdf
- Chapters "Problems" and "PKI"