CENTRE FOR DOCTORAL TRAINING
IN CYBER SECURITY

Trusted Infrastructure ‘101’

Andrew Martin

TIW 2013

TC 101: Roadmap

- The challenge
  - potential failures of my PC and other devices
  - threat model
- Dimensions of the solution
  - what is trust about?
  - principles for engineering trust into a system
- Building blocks
  - hardware and software components
  - requirements of a trusted OS
- Existing Technology
  - components
  - ecosystem

The challenge:
Shall I trust this?


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LATEST: Police charge Michael Adebolajo with murder of Drummer Lee Rigby in Woolwich - the second man to be charged
Man charged over Woolwich murder
A second man, Michael Adebolajo, is charged with the murder of Drummer Lee Rigby in Woolwich, south-east London.
Protesters pack Istanbul square
Thousands of people flood into Istanbul's Taksim Square as police withdraw, the latest step in days of protests sparked by plans to develop a park in the Turkish city.
Thousands gather in square
In pictures New clashes
Matt Smith to leave Doctor Who NEW
Doctor Who star Matt Smith is to leave his role as the Doctor, the BBC announces.
Watch/Listen
New deadly tornadoes hit Oklahoma
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Possible approach to trusted computing?

Scenario: running *gcc*

- checking that I installed the right ***gcc*** package

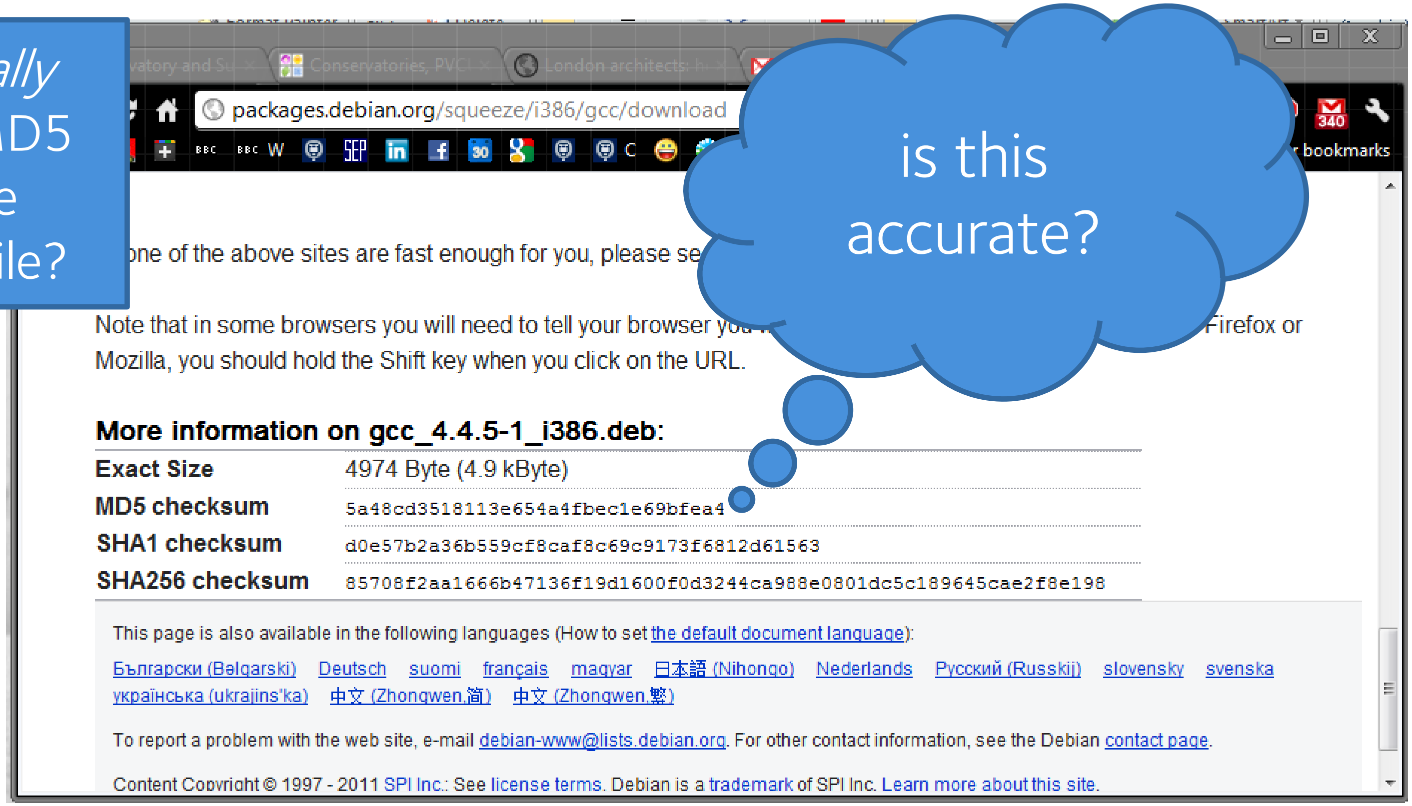
- could use a package manager…
- could do the steps manually

- ***objective***: am I installing the ‘right’ gcc

```
$ wget http://ftp.uk.debian.org/debian/pool/main/g/gcc-defaults/gcc_4.4.5-
  1_i386.deb

$ md5sum  gcc_4.4.5-1_i386.deb
5a48cd3518113e654a4fbec1e69bfea4          gcc_4.4.5-1_i386.deb
```

is this *actually* making an MD5 sum of the nominated file?



is this accurate?

```
$ wget http://ftp.uk.debian.org/debian/pool/main/g/gcc-defaults/gcc_4.4.5-1_i386.deb

$ md5sum gcc_4.4.5-1_i386.deb
5a48cd3518113e654a4fbec1e69bfea4        gcc_4.4.5-1_i386.deb
```

is the shell behaving as I expect?

am I executing **/usr/bin/md5sum** ?

is this *actually* making an MD5 sum of the nominated file?

is **/usr/bin/md5sum** the same binary that was installed originally?

does the supplied binary correctly compute MD5 sums?

Regress

```
$ which gcc
/usr/bin/gcc

$ md5sum /usr/bin/gcc
72efc7342fd5bc5c99bc3d97aef3ef

$ /usr/bin/md5sum /usr/bi
a664b65ed7b67aa489              /usr/bin/md5sum
```

Read Reflections on Trusting Trust,
By Ken Thompson

- verifying t the correct operation of the utility
- ve relies on the correct operation of the she OS
- verif the correct operation of the OS relies on … *lower level stuff*
- what am I really relying on?

Layering our security

- layered approaches pervade our computer systems architecture
  - commoditization is key
- we have many approaches to security …
  - different at each layer
- correctness and verification have their place
  - but are insufficient alone
- malware operation:
  - change the machine code
  - change the context (calling stack, etc., interrupt services)
  - change the configuration

Threat model

Software-based attacks, delivered by network

- using published APIs; exploiting vulnerabiliites

Software-based attacks, delivered by other devices, with physical access

- peripherals, boot media, …

Limited hardware attack

- “things that involve opening the case”

Full, in-depth hardware attack

- “major lab facility”

Threat model

Software-based attacks, delivered by network

- fully in-scope: significant for almost all internet users

Software-based attacks, delivered by other devices, with physical access

- largely in scope, but have regard to the duration of the access

Limited hardware attack

- largely out of scope

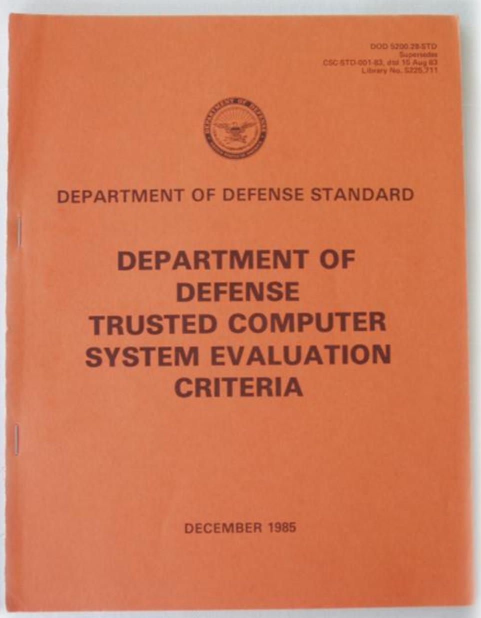
Full, in-depth hardware attack

- the classical well-funded adversary – will succeed

Dimensions of the solution:
What characteristics are needed in order to trust a system?

Trusted Computing Base

The Trusted Computing Base (TCB) of computer system is "the totality of protection mechanisms within it, including hardware, firmware, and software, the combination of which is responsible for enforcing a computer security policy." [Orange Book]



- *what should be the design goals for the TCB?*

“Attack surface” - PC

- pre-boot (BIOS, UFEI)
- firmware, option ROMs
- management functions (SMM, SMI)
- OS kernel
- kernel-mode drivers
- application software and drivers
- peripherals
- etc.

Steps to Trust

Graeme Proudler says it is safe to trust something when:

- it can be unambiguously identified, and
- it operates unhindered, and
- the user has first-hand experience of consistent, good, behaviour
- or the user trusts someone who vouches for consistent, good, behaviour.

Steps to Trust

Graeme Proudler says it is safe to trust something when:

An entity can be trusted if it always behaves in the expected manner for the intended purpose.

(TCG 2004)

RFC 4949

```
trust 1. (I) /information system/ A
  feeling of certainty(sometimes based on
  inconclusive evidence) either (a) that
  the system will not fail or (b) that the
  system meets its specifications (i.e.,
  the system does what it claims to do and
  does not perform unwanted functions).

(See: trust level, trusted system,
  trustworthy system. Compare: assurance.)
```

RFC 4949

trusted computer system 1. (I) /information system/ A system that operates as expected, according to design and policy, doing what is required – despite environmental disruption, human user and operator errors, and attacks by hostile parties -- and not doing other things [NRC98]. (See: trust level, trusted process. Compare: trustworthy.)

trustworthy system 1. (I) A system that not only is trusted, but also warrants that trust because the system's behavior can be validated in some convincing way, such as through formal analysis or code review. (See: trust. Compare: trusted.)

Beware

Words like 'Trust' get some… ople
very excitable. Our ob… re
*is **not** to explore… phy,*
sociology, o… ology of
trust, … the term as a
sho… a particular collection
…sonably well-defined
technical concepts.

Read Why Trust is bad for Security
By Dieter Gollman

Nomenclature

Some people now regret the name *Trusted Computing*:

Trustworthy Computing could be a better title,

or maybe *Trustable Computing*

but it's too late to change.

Which is the better name?

Building Trust in a System

we want to gain maximum benefit from the *hard-to-alter* characteristics of hardware

need a cost-effective engineering solution

we want to factorize the *trusted computing base*

focus for now on the identification and unhindered operation of systems

Kinds of solution

all code in ROM/gates;

- does the same thing forever

code in firmware;

- can be updated

critical functionality in ROM, firmware;

- general code in software

fully (re-) programmable system

A goal

- We want to achieve hardware-like trust characteristics in a software programmable system.
  - implement hardware-based roots of trust
    - control secret keys
    - control platform identity
  - build chains of trust which indicate/manage what software is running
    - report *platform state* reliably
    - and/or launch only white-listed software

Extending a Trust Perimeter

secure element (SE)

- limited-functionality hardware, (relatively) highly assured
- TPM, Smartcard, crypto processor., UICC ..

trusted execution environment (TEE)

- more general-purpose code execution platform
- uses secure element and other hardware to deliver evidences of trustworthiness (identity, normal operation...)

* I may be stretching terminology a little

Roots and Chains

root of trust

- also called *trust anchor:* A component that must always behave in the expected manner, because its misbehaviour cannot be detected. The complete set of Roots of Trust has at least the minimum set of functions to enable a description of the platform characteristics that affect the trustworthiness of the platform. [TCG]

chain of trust

- Iterative means to extend the trust boundary from the root(s) of trust, in order to extend the collection of trustworthy functions. Implies/entails transitive trust. [TCG, paraphrased]

Making this manageable

- resets and updates
- supply chain management
- points of control: who decides what's trustworthy?
- using crypto: key management and global secrets
- commoditization *vs* specialized solutions
- respect free markets/competition law
- verification, proof, assurance, evidence
- privacy

Building Blocks:
What kind of tools do we have?

Protected Storage: identity and more

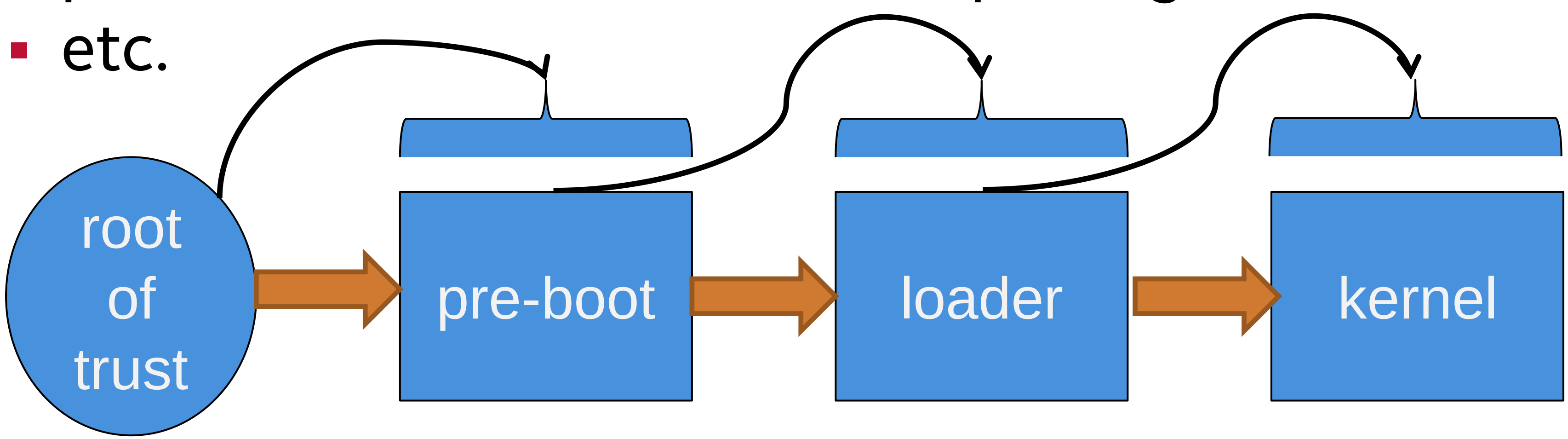
- protected storage for keys
- prevent secret key from being exported
- use key for controlled purposes
  - encryptions, decryptions, signatures, proof of possession ...
  - subject to access control
- one key – uniquely identify the device holding it
  - (and the platform, if the device is permanently attached)
  - might be bad for privacy
- multiple keys and indirection solve this problem

Protected Storage: identity and more

- extended functionality allows hierarchy of keys/keychain
  - including multiple identities, sub-trees for different users/processes/purposes
- all insufficient alone: bad software could invoke all this functionality
  - but cannot, say, clone the device/platform

Trustworthy/Known State

- controlling the platform boot is a good way to ensure normal operations
- immutable root of trust checks pre-boot before passing control
- pre-boot checks loader before passing control
- etc.



- what’s wrong with this?

Key management is tied up with state management

- access to certain keys will be tied to particular states
  - updating ‘good’ reference values
  - managing keys for platform identity
  - preventing one layer from impersonating another
  - doctrine of defence in depth implies we should not simply assume that trusted software is trustworthy

Achieving Trusted Execution

separate trusted co-processor	• critical code run in a separate contained environment
dual (or multi-) mode processor	• critical functions, I/O etc., only available in trusted mode; typically trusted mode manages the boot process
measured boot	• make a tamper-proof record of the boot process, so higher level code has evidence of the functionality it relies upon
secure boot	• check each element contributing to the boot process, and halt (or enter a special state) if a bad one is found
late launch	• special processor instructions put the platform into a controlled state, then transfers control to assured code, achieving strong isolation for this

Deciding what to launch

- launch-time checking of a whitelist
  - cryptographic hash of object code
- digital signatures on object code
- limits on the installation of code
  - app store model

- this doesn't inhibit malware which launches within the 'good' code's execution environment
  - e.g. return-oriented programming
- time-of-check-time-of-use (TOCTU) problem
  - is the code which is executing the same code that I checked?

Hardware Access Lock: ratchet approach
(IBM 4758)

- special ratchet register set at zero at system reset
- can only be incremented (up to a maximum value)
- read/write permissions for some memory blocks determined by ratchet value
  - higher value ~ lower trust ~ less access

- reset starts ‘Miniboot 0’ – resides in ROM
- termination of Miniboot 0 increments register and calls Miniboot 1 (can check its integrity first)
- termination of Miniboot 0 increments register and calls OS Kernel (say).
- etc.

TCG approach to Trustworthy state for a computing platform

essence is to take a **measurement** (a *cryptographic hash*) of each component which contributes to the platform state

- firmware, kernel, library, application binary, configuration file, etc.

use those measurements as the basis of deciding if the platform is in a state I trust

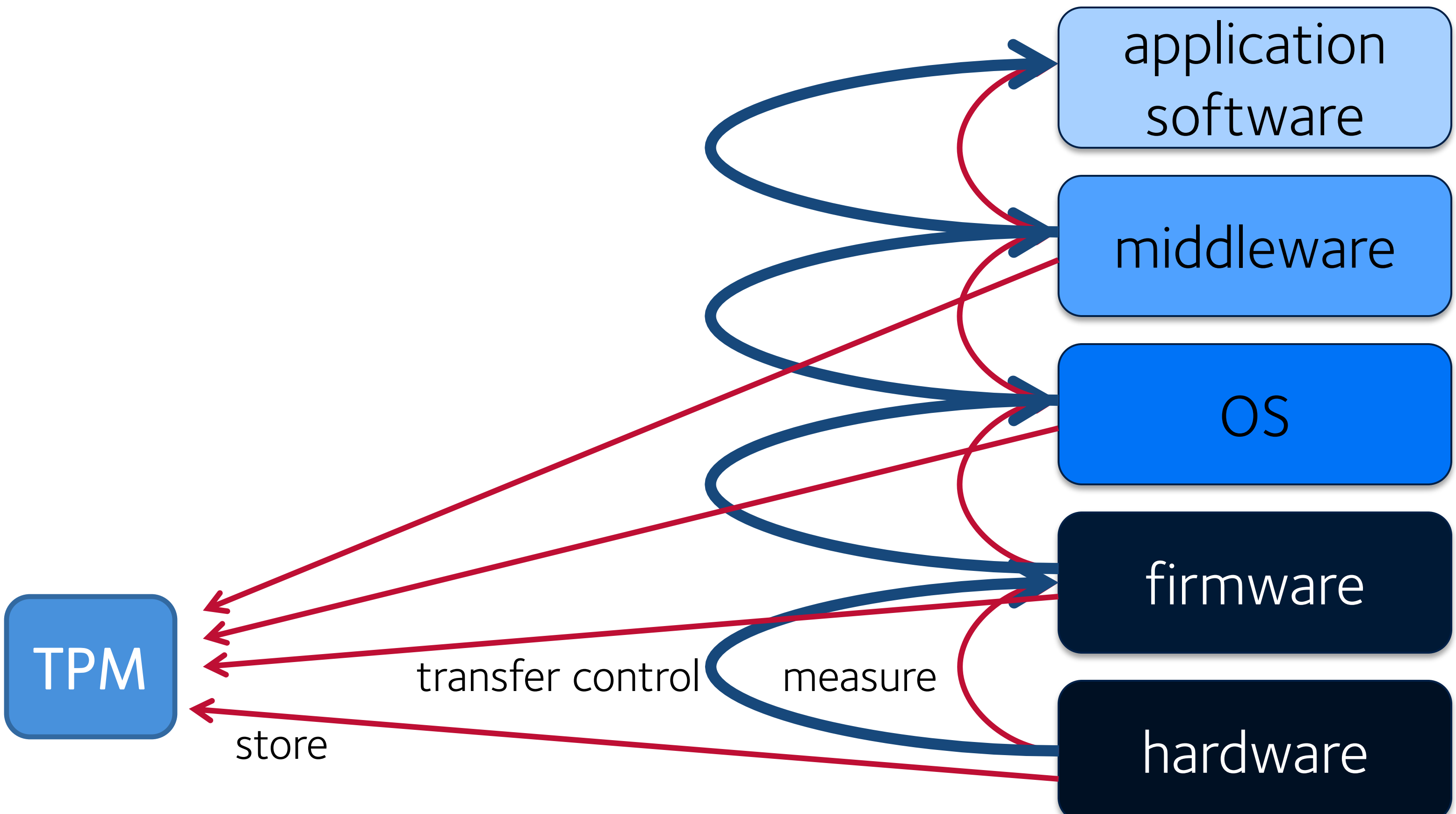
- the same state as last time it booted
- using components without known vulnerabilities
- etc.

Building a record of platform state

- is my application untainted?
- is the environment in which it runs untainted?
- how to obtain measurements?

Building a record of platform state

- concept is to have each component in the chain be *measured* by the preceding one



Trusted Computing Group PC Architecture: Roots of Trust

Root of Trust for Measurement **(RTM)**

- initiates process of recording what software is running
- e.g. implement in BIOS: in an immutable or securely updatable component

Root of Trust for Storage **(RTS)**

- implements shielded locations: registers with special integrity or confidentiality characteristics
- implement in Trusted Platform Module (TPM): in hardware for tamper-proofing

Root of Trust for Reporting **(RTR)**

- using cryptography to give assurances to third parties
- built from keys burned into TPM at manufacture time

Remarks

- this process gives us a *measured* bo[…]ocess
  - any component in the chain can […]e about the components below/bef[…]e TPM
  - implies *transitive tru*[…]
- considerable co[…]
  - around […]al boot to a ge[…]tem
- […]onvert this to a *trusted* (…

Read *On the Feasibility of Remote Attestation for Web Services*
By John Lyle and Andrew Martin

Attestation

Record of platform state can *attest* that state to other code on the platform.

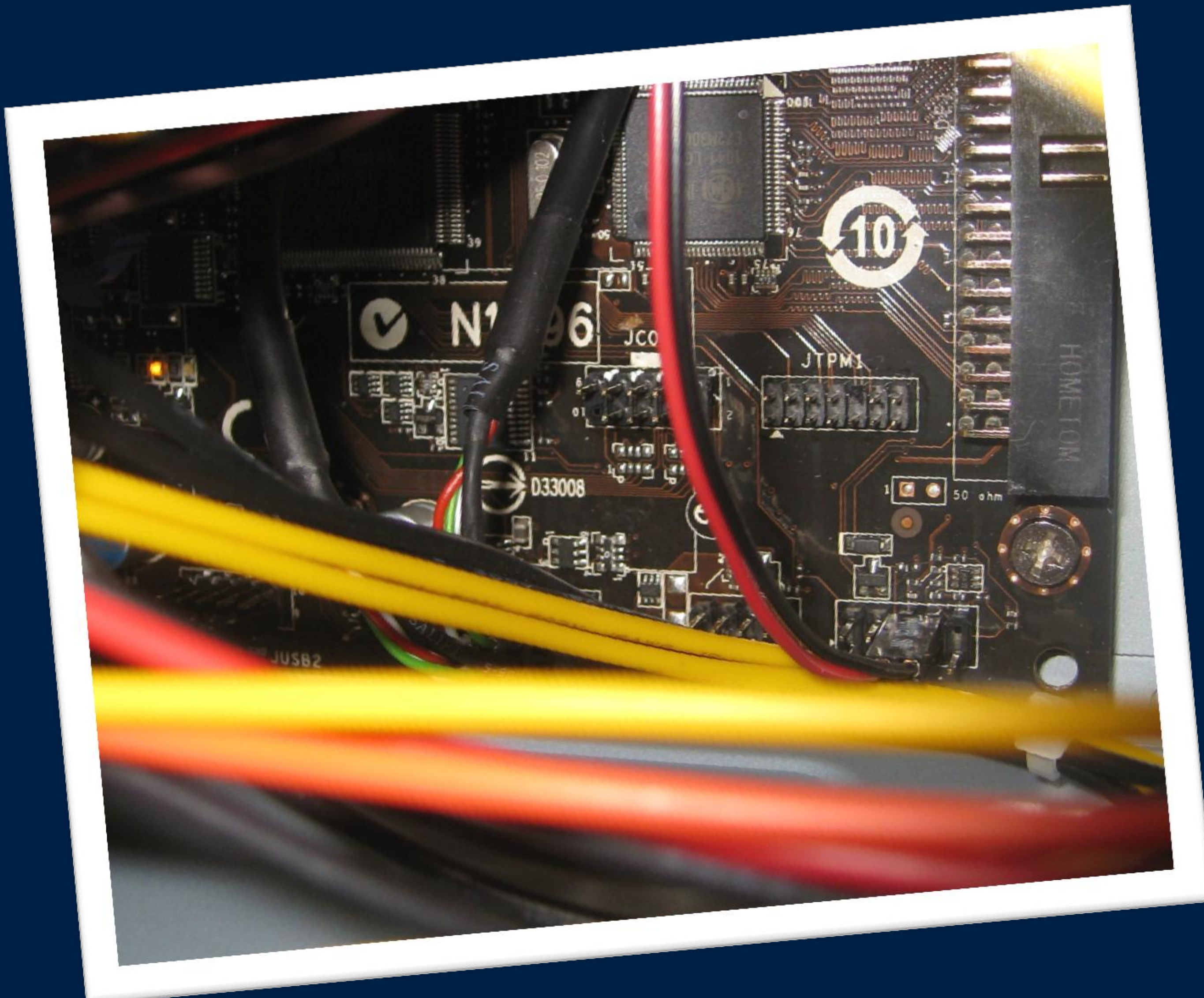
careful thought needed regarding how to make use of this

It can also be used to demonstrate to a third party that the platform is in a particular state.

this is ***remote attestation***

Existing Technology:
What can I pick up and use?

Missing piece



Role of TPM in measurement

Provides tamper-proof store for measurements

- we can record additional measurements, but not overwrite old ones, nor undo their recording, without a platform reset

Needs to provide authenticated reports, too

- consider an application asking a TPM driver to report on the platform state
- driver could lie to application, unless TPM output is itself strongly authenticated
- how to communicate this to the desktop user?

TPM: Core Functionality

- non-volatile storage:
  - storage root key (SRK)
  - endorsement key (EK)
  - monotonic counters
- volatile storage :
  - other keys
  - context, authentication sessions, secure transport sessions, ...
  - *platform configuration registers* (PCRs)
- computational functions
  - crypto, ('true') random numbers, key generation
- ***shielded locations – protected capabilities***
  - *deliberately not a Turing Machine!*
  - controlled interface to keys and PCRs

Platform Configuration Registers (PCRs)

implement trustworthy storage of *measurements*

- output of *hash* function
  - hash of program code
  - hash of configuration file
  - hash of password (if needed)

cannot be directly *written*, only *'extended'*:

$$extend(i, v) := \quad pcr[i] \leftarrow hash(pcr[i], v)$$

Reading Platform configuration registers (PCRs)

PCRs

- cannot be directly *written*,
- but can be *read*

PCR read operation:

TPM PCRRead(n) :=
output *PCR[n]*

PCR *'quote'* operation, for nonce *i*:

TPMQuote$(\{n_1, \ldots n_m\}, i, auth, k) :=$
output $(\{PCR[n_1], \ldots PCR[n_m], i\}_{key(k)}$

"give me a signed, current record of the contents of the PCRs nominated"

Attestation

PCR *Quote* operation enables us to build protocols which *attest* a platform's state to a third party

Nonce value allows third party to know that quote is 'fresh'

Signing key needs to be certified as belonging to a TPM and/or platform, to the third party's satisfaction

This attestation of binaries raises many problems/issues as well: often we would prefer *semantic* attestation.

Platform Identity and Endorsement

- The Endorsement Key (EK) is held in the TPM:
- gives the platform a unique identity
  - the EK is typically* fixed for the lifetime of the platform
- asserts the platform credentials:
  - secret key is the proof of possession for *endorsement credentials*, conformance, etc.
- Secret part of EK must not be known outside the TPM
  - but the specification allows it to be generated outside the chip, during manufacture
- These features give rise to significant challenges for manufacture, supply chain management, and provisioning.

TPM v1.2 detail

EK is a 2048-bit *RSA* key pair

Embedding

- Anything could *claim* to be a TPM, or a trusted platform
  - *root of trust for reporting* is intended to substantiate claims
- To trust the platform we need
  - assurance that it contains a correctly-implemented TPM
  - evidence that the embedding of that TPM within the platform conforms to an evaluated design
- Here is a role for
  - platform manufacturers
  - third-party accreditation
  - *digital certificates*

Attestation Identity Key (AIK)

- Solution to privacy problem is to allow the platform to have arbitrarily many *attestation identity keys* (AIKs)
- Process for signing these involves EK — so can check platform credentials
  - run a protocol with a *"Privacy" CA*
- In use, the AIK has no reference to EK
  - but would generally assert that this AIK belongs to *a* TPM
- Each AIK is strongly bound to the platform, and protected by the root of trust for storage (RTS)
- Alternative is *Direct Anonymous Attestation* (DAA)
  - advanced zero-knowledge protocol
  - resource-intensive; optional implementation

Hierarchy of Keys

- a storage root key (SRK) generated and held in TPM – (re-)initialized by "take ownership" (v1.2)
- private part cannot be extracted
  - can be used to *decrypt* (see below) only
- key blobs can be encrypted for storage in untrusted locations
- TPM implements 'LoadKey' operation to import an encrypted blob, and hold it in temporary store
- so TPM can protect an arbitrarily large collection of keys

Migratable and non-migratable keys

Would want to migrate keys:

- to permit *group* use of keys, in some applications
- practicality and compatibility with non-TPM software
- users move!
- because hardware doesn't last forever (*)

Would not want to migrate keys:

- to have confidence that some keys are forever bound to a particular TPM
- desirable that some keys are *guaranteed* to exist in only one place (at any one time, anyway)
- danger of keys being available outside the control of *any* TPM

Sealed Storage

- combine cryptographic capabilities with PCRs to give a novel capability: ***sealed storage***
  - ‘sealing’ operation nominates a key, target PCR values, and some data
    - target values need not be current PCR values
  - result is a *blob* which can
    - only be unsealed only the TPM which sealed it
    - can be unsealed only if the current PCR values match the target PCR values

TPM summary

- headline features:
  - shielded locations / protected capabilities
  - key storage hierarchy
  - platform configuration registers
  - crypto support; key generation; random numbers
  - other functions

TPM and TEE

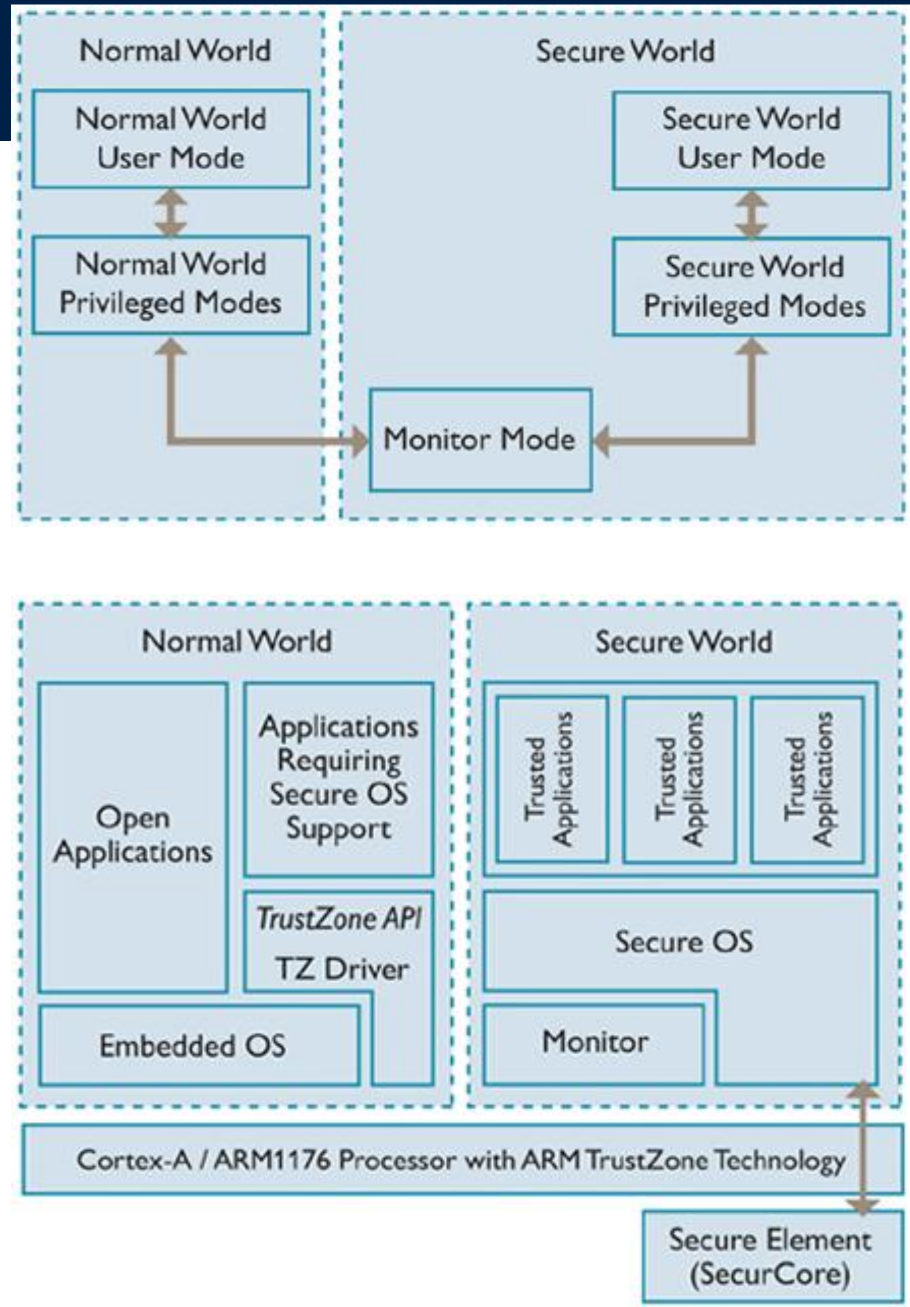
- TPM supports measured boot
  - extend PCRs with hash of each component
  - different PCRs defined for different boot phases in a PC
- TPM supports late launch
  - high-numbered PCRs reserved for recording hashes of late launched environment
  - major vendors implement processor/chipset capabilities to enable this
- Mobile TPM uses secure boot
  - mobile platforms have special requirements

What is late-launch good for?

- launch a secure hypervisor
  - use it to measure a virtual machine; gives trusted virtualization
  - many complexities around I/O and drivers
- launch a tiny OS/‘shim’/execution environment for a particular task
  - key verification; signature-making; etc.
  - none of your normal OS functionality available
  - see *Flicker, TrustVisor*
- *other?*

ARM TrustZone®

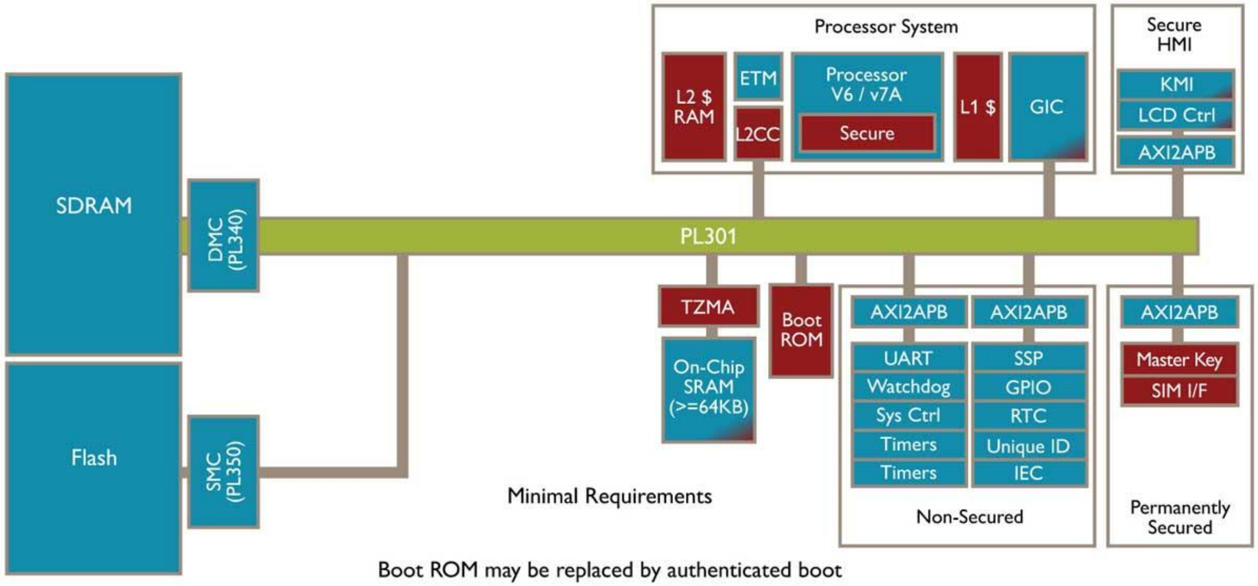
- aims for programmable environment which protects confidentiality and integrity of assets
- partition hardware and software resources into two worlds
- minimize content of secure world
- extensions allow a single core to time-slice between worlds
- transfer is via monitor mode – carefully controlled entry point
- can run whole secure OS in secure world



Images and concepts from http://www.arm.com/products/processors/technologies/trustzone.php

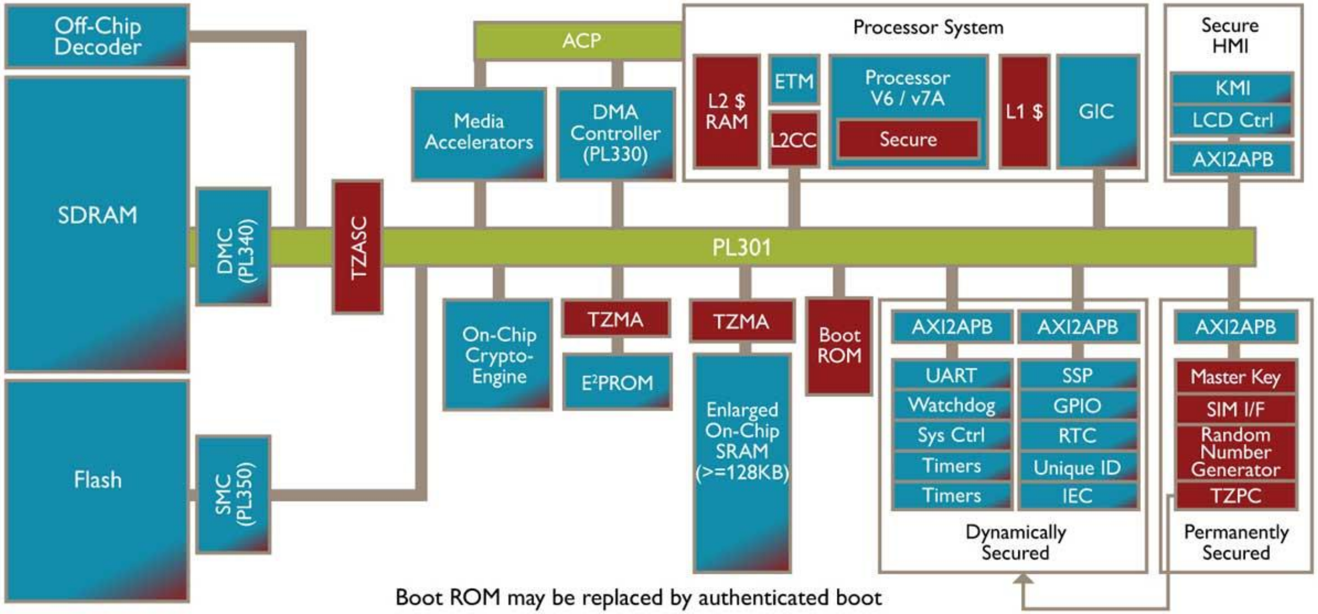
Trust Zone Tier 1

- aims to secure keypad and screen – for entering PINs, etc.
- when application requests payment, secure kernel is invoked
- secure boot via boot ROM to secure OS, then main OS
- master key and SIM (secure element) interface block tied to secure mode

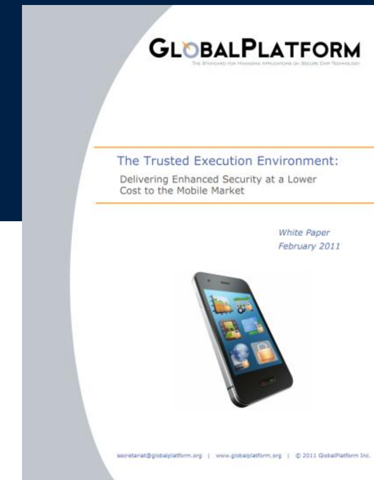


Trust Zone Tier 3

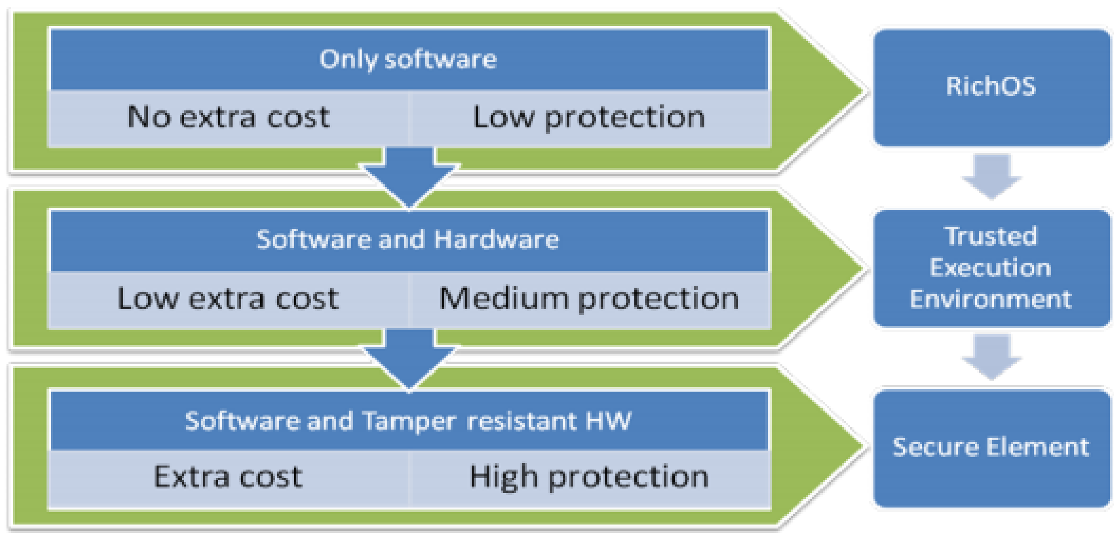
- tier 2 adds DRM capability through address space controller (TZASC)
- hardware crypto acceleration for performance
- other key management, DMA control, etc., brought into the security regime



‘GlobalPlatform’



- cross-industry standards effort
- covers multiple embedded applications on secure chip technology
- its trusted execution environment is designed as a separate zone, distinct from the rich OS of the main platform
- “considerably lower cost than an secure element”



Some other technologies

- secure UFEI
  - allows a secure boot through digital signatures
  - Windows 8 makes use of this (as well as TPM measurements, higher up the stack)
- ChromeOS
  - uses the TPM for key storage
  - implements a secure boot without critical use of the TPM

Trusted Network Connect

- whether wired or wireless – *network access control* (NAC) is a significant requirement
- TNC designed to allow access to the network to be based on attestation
- with virtual networks (VPN, VLAN) different VMs can be routed separately *based on attestation data*
- High-grade NAC with potentially low overheads.

Reflection

Trusted Computing Critics

- Early proposals for trusted computing platforms met many criticisms
  - some were clearly ill-founded
  - some have been addressed in current designs
    - widely acknowledged and accepted
  - some may persist
    - accepting that many technologies have both ‘good’ and ‘bad’ uses
  - scope for DRM was a *cause célèbre*
    - but look at our threat model...
- Criticisms deserve to be taken seriously:
  - Ross Anderson: *‘Trusted Computing’ Frequently Asked Questions*
  - Richard Stallman: *Can you Trust your Computer?*

Trusted Computing Critics

- Who decides what to trust?
  - should be platform/system *owner*, not vendor, etc.
    - private individual *or* corporate IT
    - may delegate this decision
  - but how to ensure users are not tricked/phished, etc.?
  - *AppStore* model appears to be highly effective in controlling the spread of malware.
- Highly desirable to have no master key; no global secrets
  - most of the designs we shall explore this week have this property
- Platform identity is highly sensitive
  - see discussion of privacy protections

Attacks

- Few known attacks against the functional spec
  - intention is that there should be *no* software attacks
- TPM v1.1 had a reset attack in the PC platform
- In just about *every* system, the TPM is *not* going to be the weakest point
  - attacks are presently of largely theoretical interest
- Attacks against the secret keys are expected to require large physics lab capabilities
  - one attack (Feb 2010) achieved this
  - Question: what is the impact of such an attack?
- *Question: besides attacking the TPM itself, how else might we compromise the operations it is intended to protect?*

Threat model revisited

- The threat landscape has evolved considerably since this kind of trusted platform was first proposed.
- We should keep asking:
  - Are we looking in the right place?
  - Adopting these technologies will shift the attacks to the next-weakest spot: how well protected is it?
- see: Rolf Oppliger and Ruedi Rytz, *Does Trusted Computing Remedy Computer Security Problems?*
  - it would be timely to write an updated paper

Sober judgement

- Making anything but the smallest delta on a commodity platform price is very hard to justify
  - Incorporating TPM (see below) was designed to be no more than a $5 delta on the price of a platform; these chips currently cost less than $1.
- How much security do you get for $5?
  - Compare with the (very high) costs of bespoke national-security-grade components.
- *But smart use of technology can magnify the investment immensely:*
  - compare with easily-implemented strong cryptography.
  - *Cost to use* vs *Cost to break* can be very favourable.

Summary

- The Challenge
- Dimensions of the solution
- Building Blocks
- Existing Technologies
- Clear thinking needed

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in CYBER SECURITY

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