# Virtual Monotonic Counters and Count-Limited Objects Using a TPM without a Trusted OS

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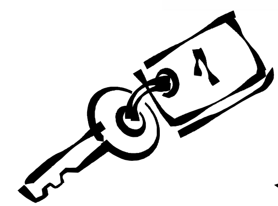
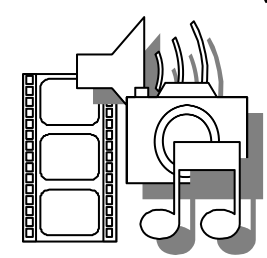
# Our Paper

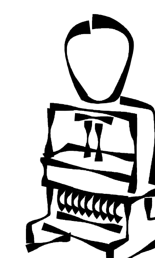
- **Monotonic Counter: A counter whose value cannot be reversed to an old value**
  - even if an adversary has complete control of the host machine containing the counter mechanism
- **Enables several <u>offline</u> (and thus highly scalable) applications:**
  - **Replay-evident Trusted Storage using Untrusted Servers**
    - where clients can be offline relative to each other
    - monotonic counters can be used for time-stamping
  - **Count-Limited Objects ("clobs") and operations ("clops")**:
    - Objects/operations which can only be used once
    - e.g., one-time or n-time use signing/encryption keys, etc.
    - Potential: DRM, offline payment (e-cash), e-voting, etc.
- **Our paper: *Virtual* monotonic counters using TPM *without* a Trusted OS**
- **Two solutions**
  - Log-based scheme (works with TPM 1.2, but has drawbacks)
  - Hash-tree based scheme (small new proposed TPM functionality)
    - More efficient, and allows count-limited objects and operations

# Count-Limited Objects and Operations

- **Objects or commands which an untrusted host can successfully use/execute only a limited number of times**
  - even if host can keep and replay old objects and data
- **Examples and Applications**
  - **n-time-use delegated signing/encryption keys**
    - Alice gives Bob a token which lets Bob to sign/encrypt using Alice's key n times
    - Useful for **n-time offline authorization, authentication, encryption**
    - Potential: **e-tickets**, **e-cash**, etc.
  - **n-time-use decryption keys**
    - Bob can decrypt using Alice's key n times
    - Potential: DRM, **Personal DRM**
  - **shared-counter limited-use objects/operations**
    - Several different objects share the same counter
    - **n-out-of-a-group** operations
    - **Interval-limited** (including **time-limited**) operations
    - **sequenced** and **generating** clobs/clops
  - **n-copy migratable / circulatable objects**
    - Users can transfer an object to another user
    - BUT at most n users can use the object at a time
    - Potential: ***circulatable* DRM** tokens, e-cash, etc.
  - **count-limited (or *counter-linked*) operations**
    - Operations / functions / algorithms in general whose behavior and output depend on values of certain monotonic counters
    - Potential: **secure delegated time-stamping**, **mobile agents**, **outsourced execution**, etc.





# How Can We Implement Count-Limited Objects?

- **Three general approaches**
  - **Online Trusted Third Party**
    - Used in software/media licensing, online payments, etc.
    - Not always possible. Not scalable. Not topic of this paper.
  - **Cryptography**
    - Detect and trace double-spending (> n-times use)
    - Works for certain applications
      (e.g., e-cash, n-time anonymous authentication, etc.)
    - But, cannot *prevent* double-spending at time of offline transaction
  - **Using Trusted Component**
    - Require trusted component to produce results
      - can be hardware, software or combination
    - Trusted component securely counts usage of object
    - Actually prevents double-spending at time of offline transaction
    - But, assumes trusted component is not compromised
- **We follow the third approach, but using *only* a TPM**
  - Minimize trusted computing base

# Count-Limited Objects using Monotonic Counters

- **Note: We need to keep trusted *independent* state for *each object***

- **such as … a *dedicated* monotonic counter *per object***
  - Irreversible, non-volatile register
  - Needs to be implemented using secure internal non-volatile memory

- **Problem:**
  - It is hard to have a lot of secure NVRAM in a small secure chip
    - small space inside trusted chip
    - wear-out problem
  - So, existing secure chips only support a few monotonic counters

- **Example: Built-in (aka Physical) Monotonic Counters in TPM 1.2**
  - TPM 1.2 chips can create and keep track of at least 4 independent monotonic counters
  - BUT … can only increment 1 per boot cycle (!)
  - Allowed to throttle increments to once every 5 seconds, good for 7 years

# Virtual Monotonic Counters <u>with</u> Trusted OS

- **If we have a trusted OS or trusted software, then keeping a large number of monotonic counters is straightforward**
- **Example: TCG/Microsoft scheme for "virtual monotonic counters"**
  - Trusted OS keeps track of an arbitrary number of *virtual* counters
  - To increment a virtual counter:
    * OS increments global physical counter
    * OS "seals" the new virtual counters' *collective* state together with counter's value as timestamp (can only be decrypted by TPM when Trusted OS is running)
    * OS stores sealed data on untrusted disk
    * OS can detect replay attacks by comparing time-stamp with current value of global counter
- **Trusted OS can also enforce Count-Limited Objects/Operations**
  - Trusted OS checks the virtual counters before executing clobs/clops
- **Current DRM-enabled devices do something similar (but not using TPM)**
  - either using trusted firmware, or obfuscated software as trusted component

# Problems with depending on Trusted OS

- **Problem: Trusted OS is a BIG requirement**
  - requires TPM
  - requires trusted BIOS (CRTM)
  - requires trusted CPU (with special features)
  - requires other hardware support
  - requires new OS, which must be fully tested
- **Can we implement trusted virtual monotonic counters using just a TPM, but *without* a trusted OS?**
- **Note: Most *real-world* TPM apps that *ordinary* people actually use *today* do *not* use trusted boot**
  - E.g., mostly use ability of TPM to protect and use encrypted keyblobs
- **VMCs and Clobs are fundamental primitives that *should* also be supported without requiring Trusted OS**
  - can even help in implementing Trusted OS's

# Our Solutions

- **Using TPM 1.2 : Log-Based Scheme**
  - Use one built-in monotonic counter
  - Use log of increment operations as a freshness proof
  - Good enough for implementing trusted storage on untrusted servers
  - Advantage: works with existing hardware
  - But has drawbacks

- **Better: Hash-tree based scheme**
  - Use Merkle Hash Tree
  - Simple Proposed additional TPM functionality
    - * 1 new TPM command
    - * 1 word (160-bits) of secure NVRAM space for root hash
  - Advantages
    - * More efficient
    - * Enables *count-limited* objects and operations
      - (with simple additional changes to other operations)

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# Log-Based Scheme (Using TPM 1.2)

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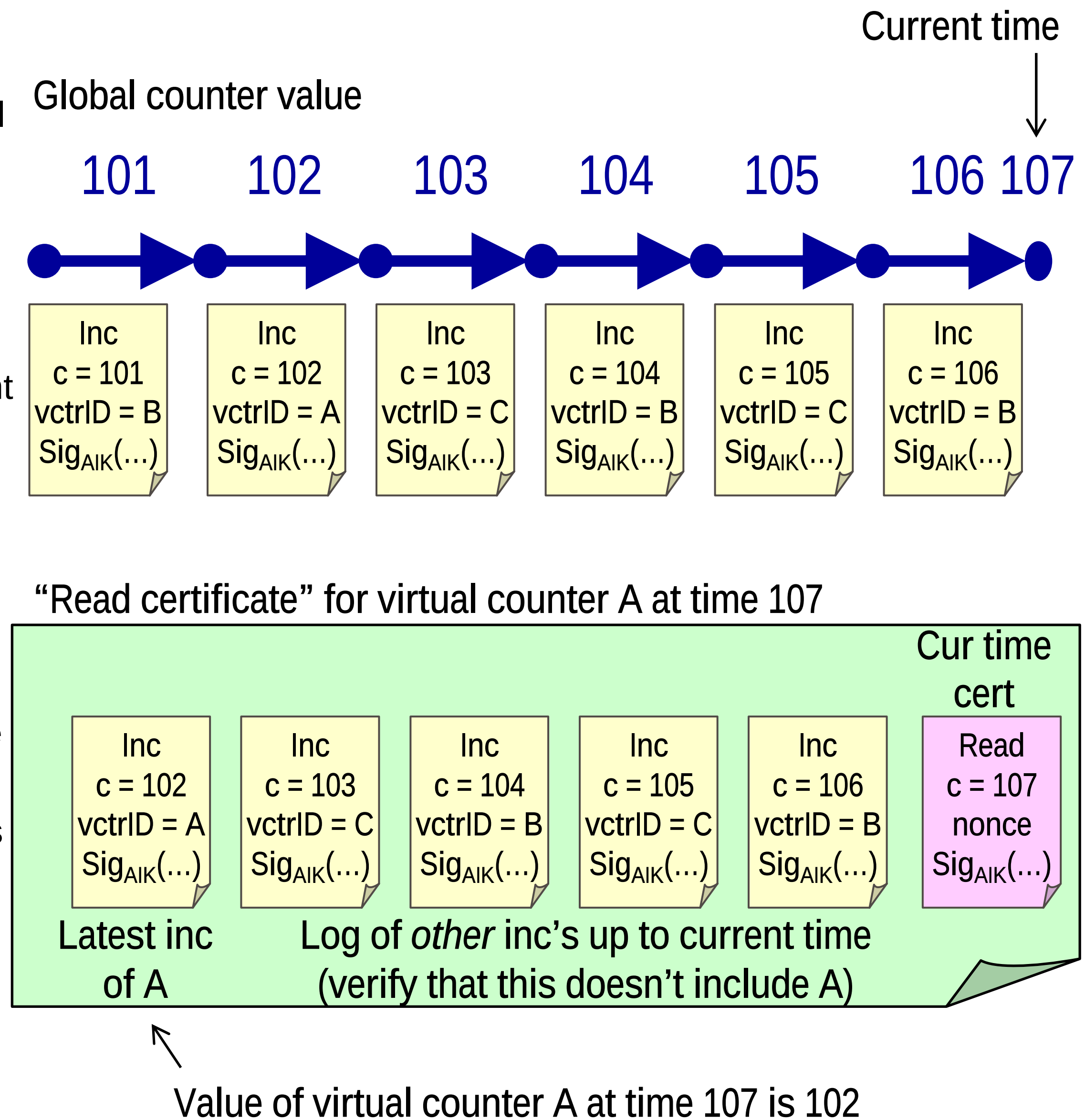
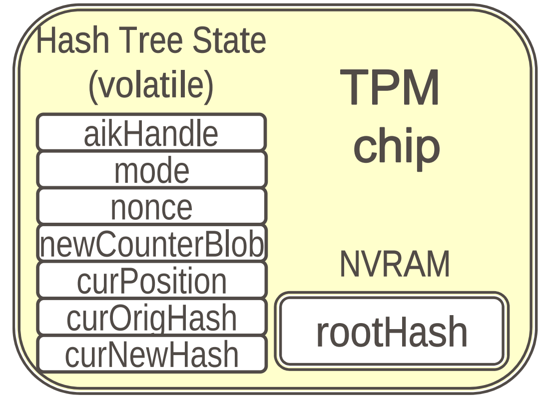
- **Idea: Use one built-in monotonic counter as global counter**
- **On increment of virtual counter A**
  - TPM does an “increment-and-sign” of global counter
    - * with nonce = H(virtual counter ID A | client’s random nonce)
- **On read of virtual counter A, client gets**
  - current global counter value
  - Latest inc certificate for virtual counter A
  - Log of inc certificates between A and current time
  - Client checks that no other increments on A were done in between
- **Drawbacks**
  - Non-deterministic
    - * Value of individual virtual counter goes up by unpredictable amounts
  - Proof of freshness grows linearly in time
    - * If a certain counter is not used while others are used a lot, then proof for that counter can become very long
  - Cannot do arbitrary count-limited operations since TPM does not limit execution
- **Useful for now**
  - Non-deterministic counter is OK for time-stamping and trusted storage
  - n-time use certificates are possible, though complex and unwieldy



# Hash-Tree based scheme

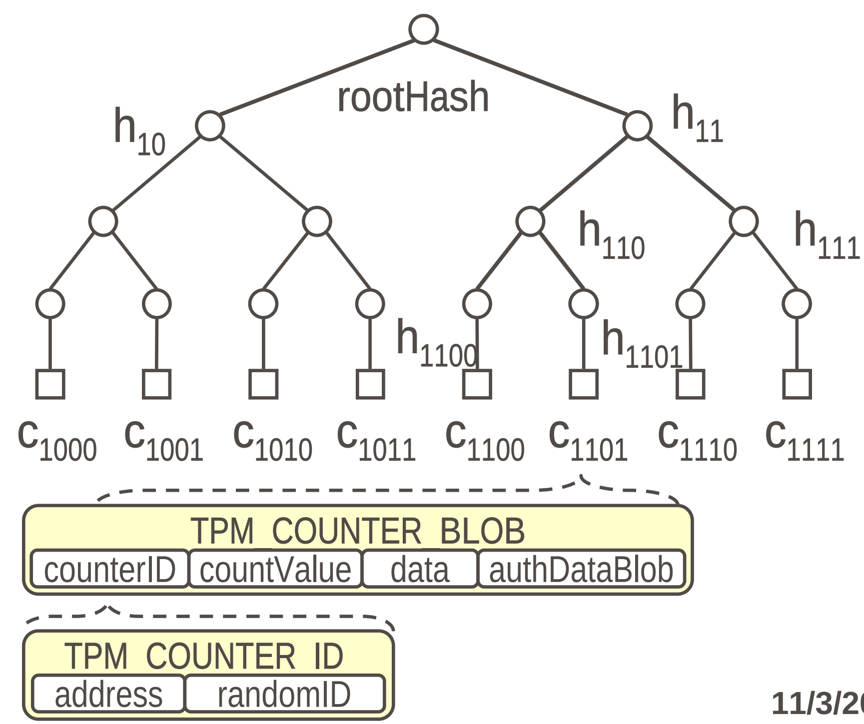
- **Each Leaf contains an individual virtual counter's state**
  - Virtual Counter ID
  - Current Counter Value
  - Other meta-data




- **Leaves and nodes are stored by untrusted OS in untrusted storage**
  - Hashes for empty subtrees are well-known, so need not be stored
    - * Allows for sparse trees

- **Root hash is kept by TPM in trusted internal NVRAM**

- **All reads, updates, and secure use of virtual counters must invoke TPM as final step**



# Proposed New Command: TPM_ExecHashTree

**Command:** TPM_ExecuteHashTree
**Inputs:** int *aikHandle*, byte *mode*
TPM_COUNTER_BLOB *counterBlob*
TPM_NONCE *nonce*
TPM_DIGEST *stepInputs*[]
(optional) byte[] *command*
**Outputs:** If successful, returns TPM_HASHTREE_EXEC_CERT
(or output of *command*)
Else returns error code
**Actions:**

1. Check authorizations for the AIK, for *counterBlob*, and for *command* and ABORT on failure (i.e., return error code and clear *hts*)
2. Check *mode* and ABORT if illegal
3. Check *counterBlob.counterID.address* and ABORT if illegal

4. *HASHTREE_START* routine:
   Initialize the Hash Tree State
   a. Create a new TPM_COUNTER_BLOB, *newCounterBlob*
      i. Copy *all* fields of *counterBlob* to *newCounterBlob*
      ii. if *mode* is INCREMENT then
         (1) *newCounterBlob.countValue* = *counterBlob.countValue* + 1
         (2) *newCounterBlob.data* = *nonce*
      iii. else if *mode* is CREATE then
         (1) *newCounterBlob.counterID.randomID* = new random number
         (2) *newCounterBlob.countValue* = 0
         (3) *newCounterBlob.data* = *nonce*
         (4) *counterBlob* = null // *old blob should have been null*
   b. Setup TPM's internal Hash Tree State for leaf node
      i. Let *hts* be the TPM's internal Hash Tree State
      ii. Set *hts.aikHandle* = *aikHandle*
      iii. Set *hts.mode* = *mode*
      iv. Set *hts.nonce* = *nonce*
      v. Set *hts.newCounterBlob* = *newCounterBlob*
      vi. Set *hts.curPosition* = *newCounterBlob.counterID.address*
      vii. Compute *hts.curOrigHash* = Hash( *counterBlob* )
      viii. Compute *hts.curNewHash* = Hash ( *newCounterBlob* )
      ix. if *mode* is equal to RESET then
         *hts.curNewHash* = *KnownNullHashes[height of position]*
      x. *hts.command* = *command*

Notes:

1. *mode* can be READ, INCREMENT, CREATE, or RESET. EXECUTE is an option bit which can be OR'd into *mode* (usually with INCREMENT or READ).
2. EXECUTE can be used with or without *command*. If used without *command*, *hts* is remembered so it can be checked by the *immediately* following command given to the TPM

5. *HASHTREE_STEP* loop:
   FOR each *i* = 0 TO *stepInputs.length* DO
   a. *siblingHash* = *stepInputs*[*i*]
   b. *isRight* = *hts.curPosition* & 1 // *(i.e., get lowest bit)*
   c. // *Set hts "current" state to refer to parent*
      if (*isRight* is 0) then
         *hts.curOrigHash* = Hash( *hts.curOrigHash* || *siblingHash* )
         *hts.curNewHash* = Hash( *hts.curNewHash* || *siblingHash* )
      else
         *hts.curOrigHash* = Hash( *siblingHash* || *hts.curOrigHash* )
         *hts.curNewHash* = Hash( *siblingHash* || *hts.curNewHash* )
   d. *hts.curPosition* = *hts.curPosition* >> 1 (right shift)
6. Check if computed original root hash is same as trusted root hash
   a. If ( *hts.curPosition* is not 1 )
      then ABORT // *not enough stepInputs presented*
   b. If ( (*hts.curOrigHash* is NOT EQUAL to *TPM.rootHash* )
      AND (mode is NOT EQUAL to RESET) )
      then ABORT // *original values fed in were not correct*
7. Execute command according to *mode*
   a. If ( *hts.mode* is INCREMENT )
      OR ( *hts.mode* is CREATE )
      OR ( *hts.mode* is RESET )
      then *TPM.rootHash* = *hts.curNewHash*
   b. If ( *hts.mode* does NOT have EXECUTE bit set)
      OR ( *hts.command* is null ) then
      i. Create new TPM_HASHTREE_EXEC_CERT *execCert*
      ii. *execCert.mode* = *hts.mode*
      iii. *execCert.nonce* = *hts.nonce*
      iv. *execCert.newCounterBlob* = *hts.newCounterBlob*
      v. *execCert.signature*
         = Sign( *hts.mode* || *hts.nonce* || *hts.newCounterBlob* )
         using AIK specified by *hts.aikHandle*
      vi. if ( *hts.mode* has EXECUTE bit set )
         then remember *hts* for *immediately* following command
         else erase *hts*
      vii. Return *execCert*
   c. else // *i.e., hts.mode* has EXECUTE and *hts.command* is not null
      i. Get count-limit condition pertaining to *hts.command*
      ii. Compare *mode* and *counterID* in count-limit condition with those in *hts*, and ABORT on failure
      iii. If *hts.newCounterBlob.countValue* is within the valid range in count-limit condition then execute *hts.command* and return result, else ABORT

3. For READ and INCREMENT, input counterBlob should have the current counter value. For CREATE, input counterBlob contains address and encrypted authDataBlob from owner/creator. For RESET, input counterBlob should have address of node or subtree to be reset, and encrypted authDataBlob with TPM owner authorization.

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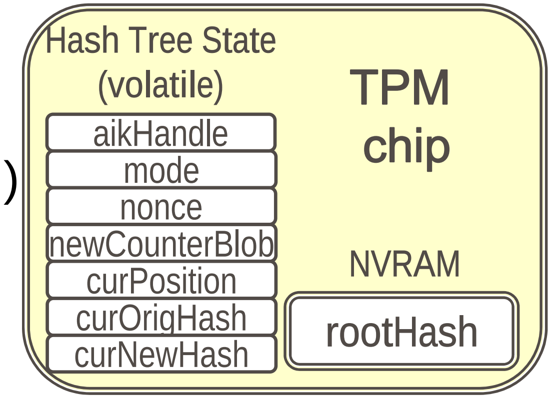
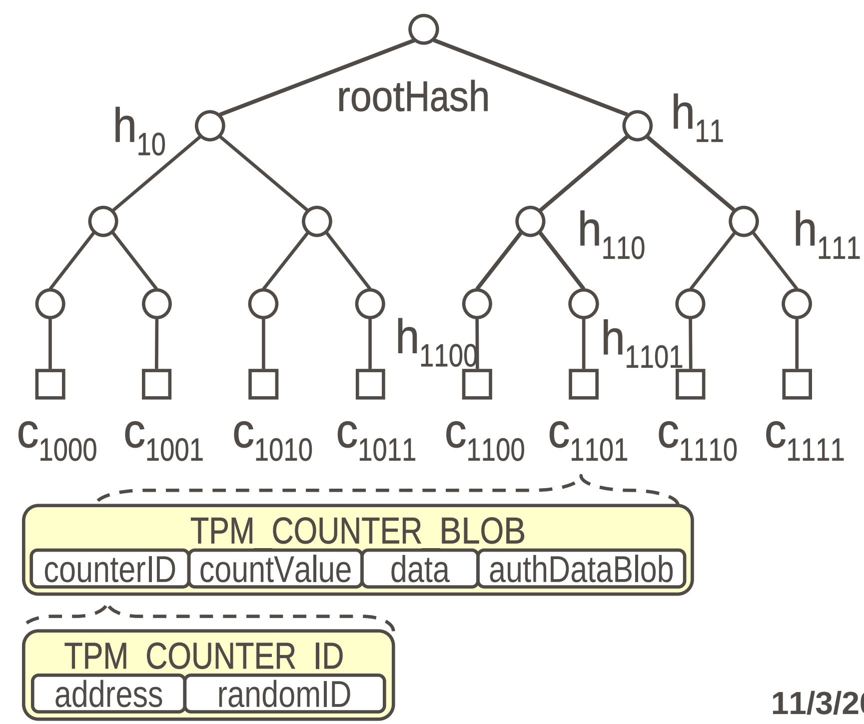
# Proposed New Command: TPM_ExecHashTree

- **Inputs**
  - AIK handle
  - mode (Read, Inc, Inc&Exec, Create,...)
  - anti-replay nonce
  - Counter Blob
  - Internal hash tree nodes
  - Optional: Wrapped command
- **Output**
  - "Execution Certificate" signed by AIK
  - OR, output of wrapped command
- **Relatively Easy to Implement**
  - 1 new TPM command
    - * plus backward-compatible modification to count-limitable operations and data structures
  - 20 bytes (160-bits) of secure NVRAM for root hash
  - All internal operations required here are already supported by TPM (e.g., hash)

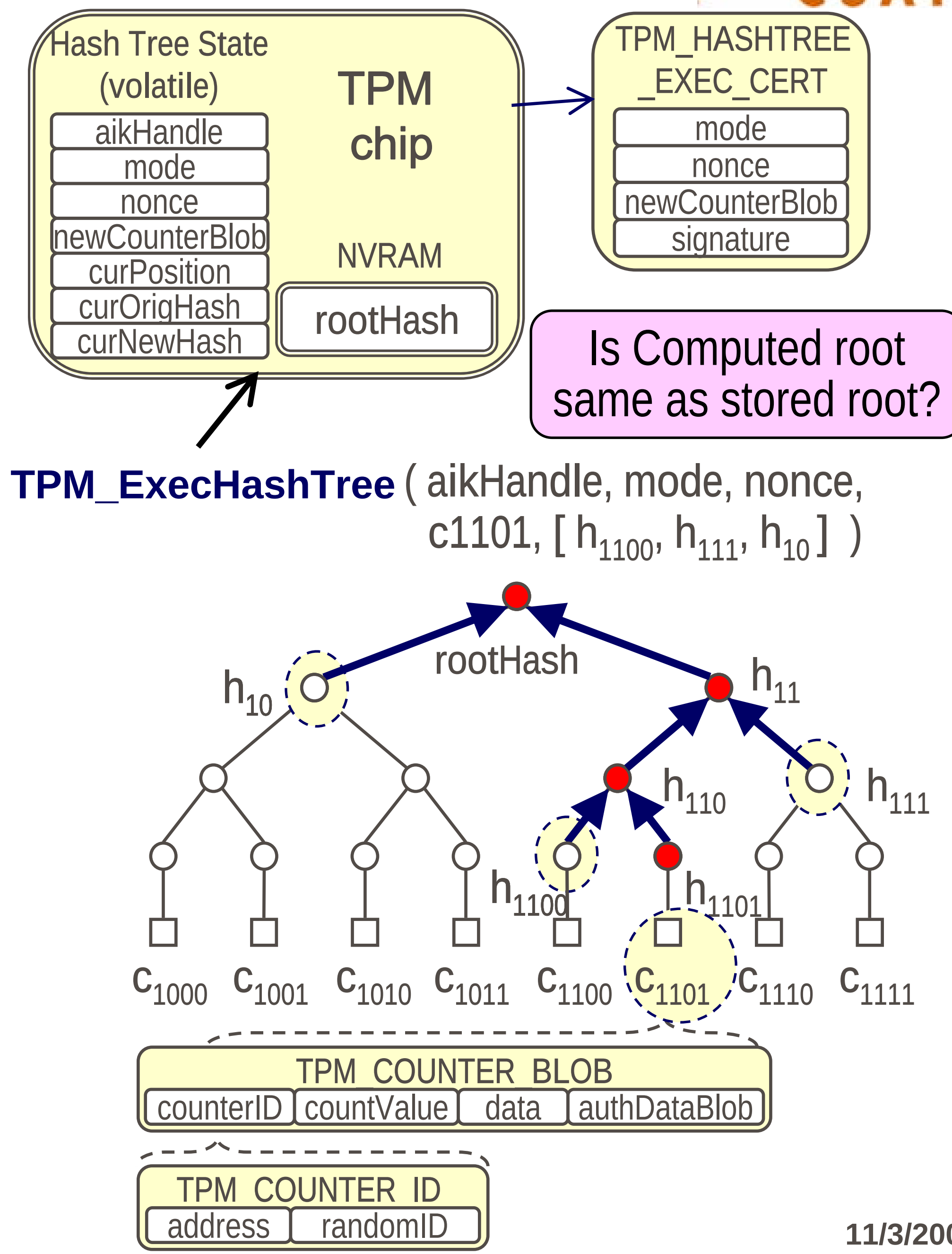


# Read Virtual Counter

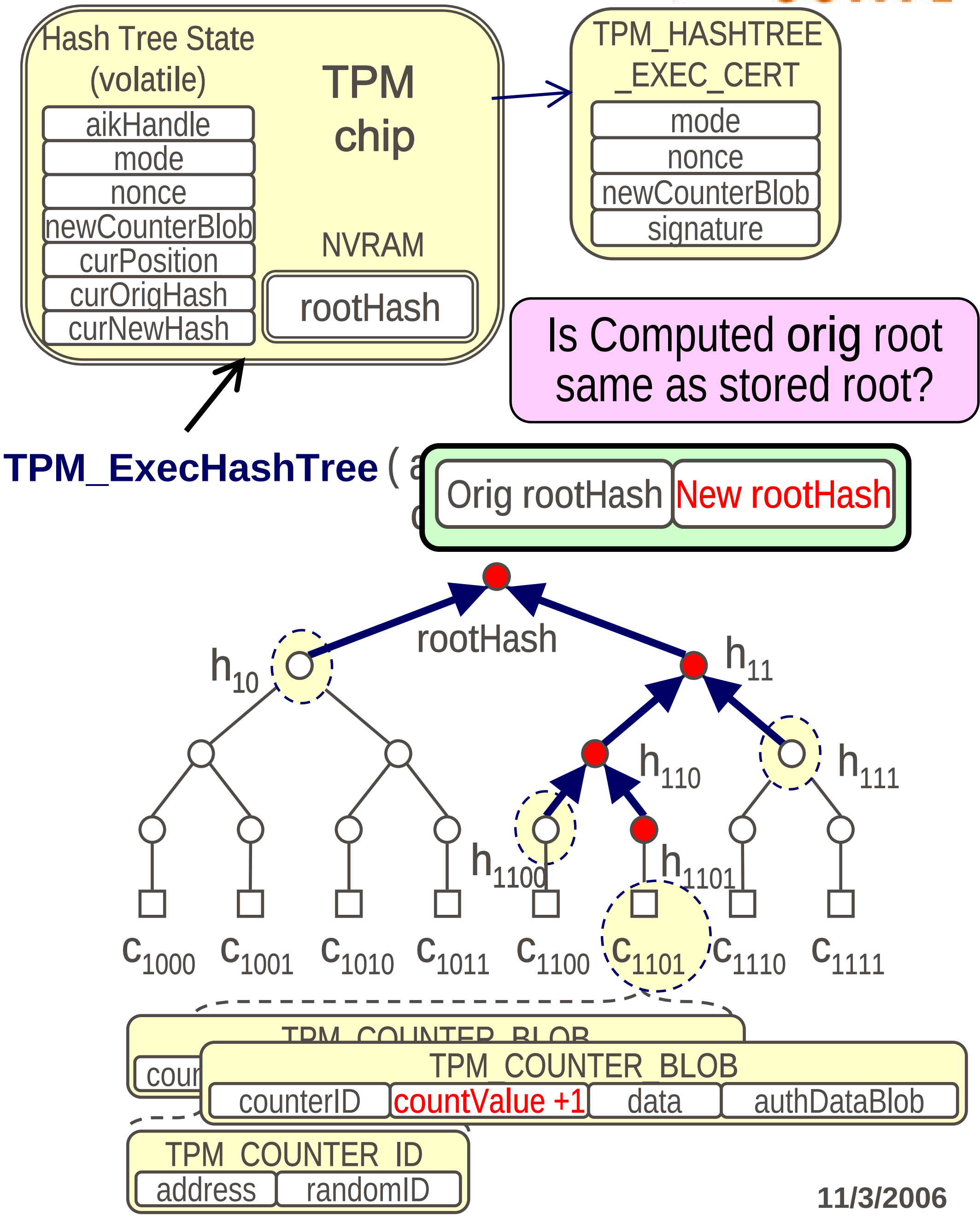
- **Host feeds TPM**
  - Counter blob
  - Internal hashes
    - * Sibling hashes on path to root
- **TPM computes root hash based on input**
  - O( log $N_{max}$ ) internal hashing operations
- **If computed root hash matches trusted stored root hash,**
  - then TPM outputs certificate (signature by AIK) certifying virtual counter blob as being fresh

- **Note: If adversary rewinds or modifies leaves or internal nodes**
  - root hash will be different
  - TPM will detect and abort



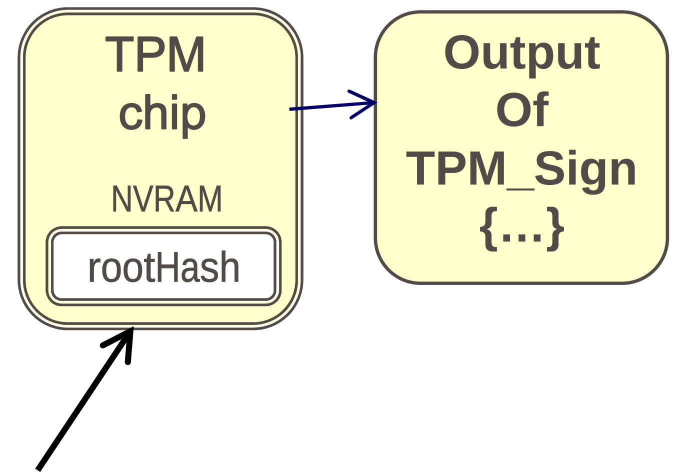
# Increment Virtual Counter

- **Same inputs as Read**
- **Difference: As TPM goes up tree, it computes *two* sets of hashes based on *two* counter values**
  - The current value
  - The new value
    - (based on counter value + 1)
- **If computed root hash based on current value matches trusted stored root hash, then:**
  - TPM updates internal rootHash with computed root hash based on *new* counter value
  - TPM outputs certificate (signature by AIK)
    - certifying that inc was done
    - Indicating and certifying new counter value



# Count-Limited Operations

- **Same input as above PLUS wrapped command**
  - Sort of like transport session
- **Mode specifies Read or Increment**
  - Normally, use increment
  - Read mode allows for objects which can be used unlimitedly until something else increments the same counter
    - * e.g., revocable key delegation
- **If computed orig root hash does not match stored root, then fail**
- **If it matches, then**
  - perform increment (if desired),
  - verify that (new) current counter value satisfies count-limit conditions of command / object
  - if so, execute command
  - Output output of command directly
    - * Optionally, wrap output in exec. cert.




**TPM_ExecHashTree**
( aikHandle, mode, nonce,
c1101, [ $h_{1100}$, $h_{111}$, $h_{10}$ ],
{ TPM_Sign(…) } )

# Count-Limited Keys

- **Existing TPM feature: wrapped keys**
  - Alice can give Bob encrypted blob containing her PK-SK keypair
  - Alice encrypts blob using Bob's TPM's storage key's PK
    - * SK of storage keypair is never revealed outside the TPM
    - * So, only TPM can decrypt and use Alice's SK in the blob
  - To use:
    - * Use TPM_LoadKey to load blob into TPM → returns key handle
    - * Use TPM_Sign, etc. with key handle
  - Note: currently, wrapped keys are NOT count-limited

- **Modifications to TPM**
  - Add **count-limit condition field** to wrapped key
    - * Includes **virtual counter ID**, **valid range**, and **allowed/required modes**
    - * Put in a variable-length field where PCR configuration is now
  - When key is loaded, condition is remembered
  - Upon doing a TPM_Sign using that key, check condition

# Using Count-Limited Keys

- **Scenario: Alice wants to give Bob a 1-time key**

- **Issuing (Alice and Bob)**
  - Step 1: Alice certifies Bob's TPM and gets Bob's storage key
    - e.g., check Bob's AIK's PK vs. known/certified value or via DAA
  - Step 2: Alice creates a new virtual counter on Bob's host
    - Bob executes TPM_ExecHashTree
    - gives new counter ID and exec certificate to Alice who verifies it
  - Step 3: Alice encrypts a key blob using Bob's storage key containing her keypair and gives to Bob
    - include count-limit condition
      - Virtual counter ID, required mode=Increment, and valid range (in this case "1")

- **Use (Bob alone, offline from Alice)**
  - Step 1: Bob uses TPM_LoadKey on encrypted key blob
  - Step 2: Bob calls TPM_ExecHashTree with wrapped TPM_Sign/TPM_Unbind/etc
    - gets relevant hash tree nodes from his storage
    - Calls TPM_ExecHashTree
    - Computes and stores new counter value and new hash tree nodes

# Applications of Count-Limited Keys

- **n-time authentication / authorization / certification**
  - Authority gives Bob a wrapped count-limited signing keypair PK-SK
    - where SK is unknown to Bob,
    - and PK is certified and verifiable as coming from the Authority
    - count-limited to n
  - When Bob needs to prove certification to Charlie
    - Charlie gives Bob a random nonce
    - Bob uses count-limited signing key to sign nonce
    - Charlie verifies Authority's signature on nonce
  - *Bob can only do this at most n times*
- **This leads to many *potential* applications***
  - Offline payment: Authority is Bank, signature has cash value
  - E-tickets (probably more feasible)
  - etc.

*** Caveat on privacy and resiliency**

# Caveats

- **Note: Anonymity can be preserved because the final output contains nothing from Bob**
  - Only Charlie's nonce, and Authority's signature
  - (Note: Charlie does not need to verify/identify Bob, because Authority's signature is enough proof)
- **Caveats**
  - #1: If Authority uses single global key, then TPMs must *never* broken
    - * If a single TPM is broken, Authority's private key is revealed. Very bad!
  - #2: If Authority uses multiple keys, then anonymity may be broken
    - * At time of issuing, Authority may give Bob a unique key, and be able to link the key to Bob's AIK (used by Authority to verify Bob's TPM)
    - * Solution (?): Use DAA at time of issuing so Authority can't link AIK to Bob
- **In the end, probably, the best solution for critical apps (e.g., real e-cash) is to use crypto-based n-time-use techniques, but use virtual monotonic counters to count-limit these in hardware**
  - e.g., implement a TPM command implementing Brand's e-cash scheme [Brands93], but store the e-coin as a count-limited object stored outside the TPM
  - Provides hardware support for immediate prevention of double-spending
    - * assuming TPM is not broken
  - AND also provides eventual traceability in case TPM is broken
- **However, simple schemes based on straightforward count-limited RSA signing operations may still be useful in non-critical applications (i.e., where the cost of breaking a TPM would be much more than the potential gain one can get by doing so)**
  - Advantage is that minimal change is needed in the TPM, and no need to define for special-purpose commands/algorithms for each application

# Other Variations on Clobs

- **shared-counter limited-use objects/operations**
  - e.g., Alice generates several *different* wrapped objects depending on the *same* virtual counter ID
  - Possibilities
    - N-times-within-a-group operations
    - Interval-limited operations
      - Can translate to time-limited if trusted clock increments counter
- **n-copy migratable objects**
  - TPM already has a migrate key feature
  - Idea: count-limit the migration
    - Assume that *usage* of key reads but does not increment counter
    - But *migration* of key increments counter
    - If Alice migrates a key to Bob, then Alice's counter gets incremented, so Alice can't use her copy anymore
    - On Bob's side, Bob gets a new key tied to a virtual counter on his TPM
    - Bob can use it until he migrates it to someone else (possibly Alice!)
  - "Lendable" objects → *circulatable* DRM, e-cash, etc.
  - Possible to make n-copy (not just 1-copy) circulatable objects
    - Circulatable but at most only n copies at any given time are usable
  - Challenge: Verification must be done by TPM (not host)
    - Verification key must be included in blob
- **Others**
  - See our MIT CSAIL Technical Report, Sept. 2006

# Other Variations on Hash-Tree based scheme

- **Split TPM_ExecHashTree into 2 commands**
  - **Start() command, followed by Step() command for each level of tree**
  - **Advantage: no need to feed all internal tree node hashes (sibling hashes) to the TPM at once**
    - works even if TPM only has small input buffer space
  - **Note: internal volatile memory requirement of TPM does NOT grow**
    - computation of hashes and updating of state is done at each step
    - no need to remember all the node hashes
    - Hash tree state is constant-sized
  - **Note: Failure before the end is not a security problem**
    - TPM state is only changed at the very last step if everything succeeds
  - **However, not clear whether splitting is even necessary**
    - we can handle 32 levels ($2^{32}$ virtual counters) with only 20 * 32 = 640 bytes for the sibling hashes
      - Even with other input data, total input size would still be much less than 4K typical input buffer space of TPM 1.2 chips
    - maybe it can be useful for 160-bit (unique) virtual counter ID's
- **Other Variants**
  - **Multiple root hashes** (allows independent hash trees, possibly of different depths)
  - **Dynamically growing hash trees**
  - **Caching**
  - **Have TPM_ExecHashTree support operations other than increment**
    - "mode" field can indicate different kinds of operations
    - e.g., Extend (i.e., one-way hash) can lead to unlimited PCR-like "hash clocks"
    - e.g., Read,Update Virtual Trusted Memory
    - This is why we recommend keeping the command name TPM_ExecHashTree generic
      - it's not limited to just monotonic counters
  - **Multiple counter operations per TPM_ExecHashTree invocation**
    - e.g., increment several counters with one TPM_ExecHashTree invocation
    - saves on time for signature operation in the end, and also saves on wear out of root hash NVRAM
  - **VMCs and count-limited objects/operations using physical monotonic counters**
  - **Count-limited wrapped commands**
    - Encrypted TPM commands with a count-limit condition field
  - **Count-limited general-purpose commands**
- **See MIT CSAIL TR 2006-064 (Sept. 2006) for details**

# Related Work

- Of course, general idea of n-time-use operations is an old idea
- Some interesting/relevant related work
  - **"Consumable Credentials" (Bauer et al. 2006)**
    * Logic for analyzing/modeling systems whose security depend on limited-use credentials
    * Currently, they assume an online trusted third party, though
  - **Cryptographic Techniques**
    * Classic e-cash, etc.: Chaum82, Brands, etc.
    * Lots of other recent work:
      - E.g., n-time anonymous authentication, etc. (e.g., CHKLM, ACM CCS 06)
  - **Using Trusted Component**
    * Practically all DRM systems fall under this category today
  - **Using combination of Crypto and Trusted Hardware**
    * e.g., Brands93 talks about "observer" that stores a special value per e-coin in trusted memory and forgets it after using the e-coin once
    * Our approach can be used with this algorithm, and would allow a much larger number of values to be remembered using very little trusted NVRAM
  - **One-time or n-time *arbitrary* programs using very simple hardware**
    * Slightly prior to us, Goldwasser et al. have proposed a theoretical scheme using very simple hardware (not a secure processor like TPM). (Not yet published.)

# Ongoing / Future Work

- **Applications**
  - Virtual Storage, Offline Payments, etc.
  - (We're starting with what we can do withTPM 1.2)
- **CLAMs – counter-linkage modules**
  - implement VMCs and clobs/clops mechanisms and ideas using other secure components in general, not just TPM
  - using other trusted hardware (e.g., smart cards, IBM 4758, AEGIS, SecureBlue, etc.)
  - or, potentially even CLAMs using obfuscated software and/or trusted OS
    - * less secure but more immediately implementable and useful
- **How can having VMCs and clobs/clops as a primitive help improve the design of future trusted modules, platforms, and software?**

# Conclusions

- **Virtual Monotonic Counters and Count-Limited/Linked Objects are small but potentially extremely useful primitives**

- **We have presented 2 solutions**
  - Using TPM 1.2 log-based
  - Hash-tree based scheme (better)

- **It would be great if TCG incorporates this functionality into the next TPM**
  - Very simple to implement
  - Potentially very powerful

# For more info

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- **MIT CSAIL TR 2006-064 (Sept. 2006) has some more details**
  - http://hdl.handle.net/1721.1/33966