Disarmament Verification

Areg Danagoulian

MIT

New START treaty, 2011 – Russia & USA

- Reduce deployed warheads to 1550 warheads each -- ~3x reduction
- How do treaty partners verify that the other side is dismantling actual warheads and not fakes? <u>They don't</u>.
- Verification: **delivery vehicles** – eas**ier** to verify.

- Problems: large leftover of non-deployed warheads
  - theft → nuclear terrorism, nuclear proliferation
  - rapid rearmament in times of political crisis

→ **Authenticate warheads, <u>without revealing classified information!</u>**

Overall View of Thrust Area

- Treaty *verification* is not the same as weapon *detection*
- The goal of verification is to confirm that an object presented as “X” is “X”.
  – Negotiate protocols to establish acceptable level for “confirmation.”
- Critical Issues:
  – clear all real warheads (completeness)
  – detect all fakes/hoaxes (soundness)
  – reveal no classified information (“zero knowledge”)

Thrust Area V Subprograms

- Verification Using Inherently Trustworthy Instruments (Univ. of Michigan)
  - SAR ADC's with non-uniform bin resolution
  - Lead: David Wehe
  - Student: Fred Buhler
  - Collaborating with: **LLNL**
- Information Barriers with Enhanced Automated Isotope Identification (UIUC)
  - Lead: Clair Sullivan
  - Student: Mara Watson,
  - Collaborating with: **DAF**
- Zero Knowledge template verification (Princeton + Yale)
  - neutron radiography → comparison to a template
  - Leads: Alex Glaser, Francesco d'Errico, Robert Goldston.
  - Student: Sebastian Philippe
  - Collaborating with: **PPPL, DAF**
- Physical Cryptographic Verification of Nuclear Warheads (MIT)
  - transmission NRF to produce a physical hash of a nuclear warhead → comparison to a template
  - Leads: Richard Lanza, Areg Danagoulian, Scott Kemp
  - Students: Jayson Vavrek, Ruaridh Macdonald, Ellie Immerman, Bobby Nelson, Jake Hecla
  - Collaborating with: **PNNL**

Verification Using Inherently Trustworthy Instruments

David Wehe

University of Michigan

Conceptual

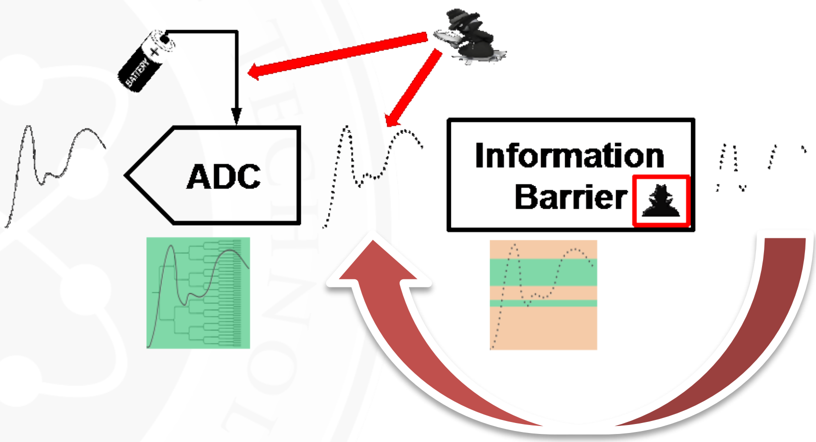
- For treaty verification, both parties must agree on a measurement protocol that provides adequate assurance that treaty obligations are met without yielding sensitive information.

- Existing approaches use templates or information barriers applied post-measurement, and are suspicious because sensitive information is acquired before the barrier.

- E.g.: FPGAs hackable, power changes detectable by untrusted observer.

- This work investigates electronic measurement techniques in which precise, spoof-proof, *digital* information can be acquired only where mutually acceptable.

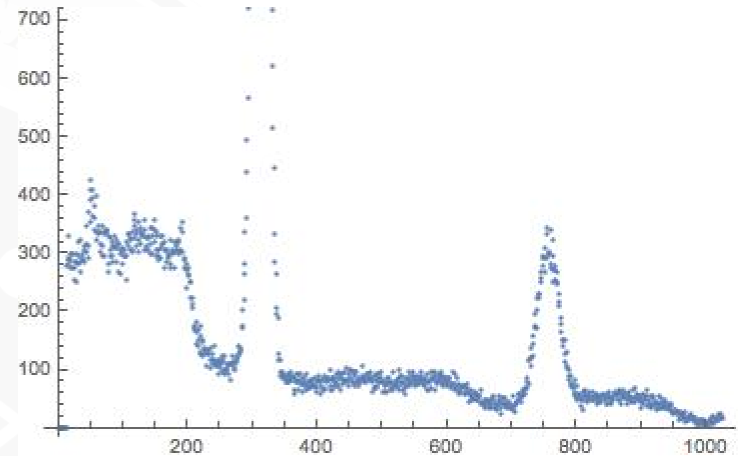
Information Flow

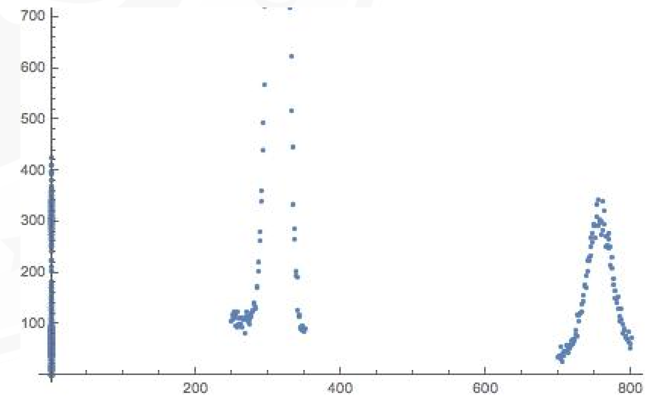


Successive Approximation

Successive Approximation ADC. Fast, high resolution.

- Pulse height is measured to a resolution of 2^{-n} after n^{th} step.
- n+1 step only taken if <u>could</u> fit into a predefined range
- High resolution in ROI, no/low information away from allowable ranges.
- Significant gain in throughput
- No measurement of irrelevant information



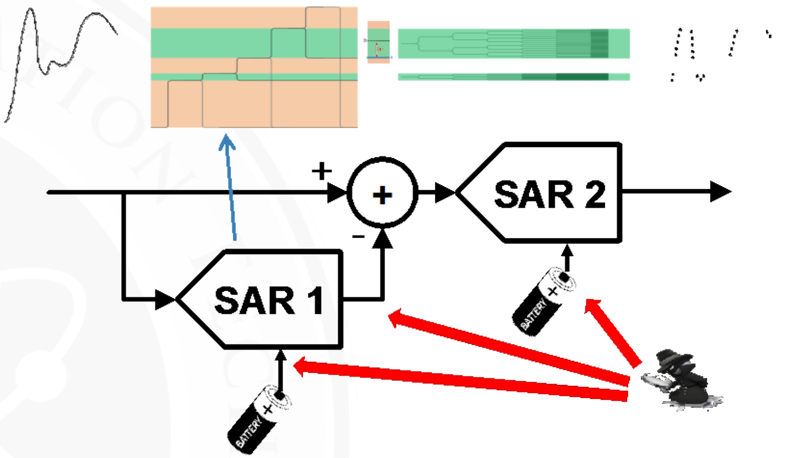


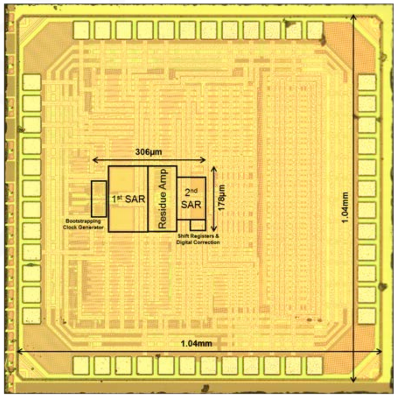
New two-stage SAR ADC archetecture

- First stage only detects if input is within
  an agreeed upon spectrum
- Error amlifier limited to
  desired window
- Second stage digitizes the error signal

Untrusted Observer Immunity: Each stage is physically (capacitor size) and electrically (saturation) limited to the agreed upon spectrum

Side Attack Immunity: SAR decision tree removes power supply correlation with ADC code



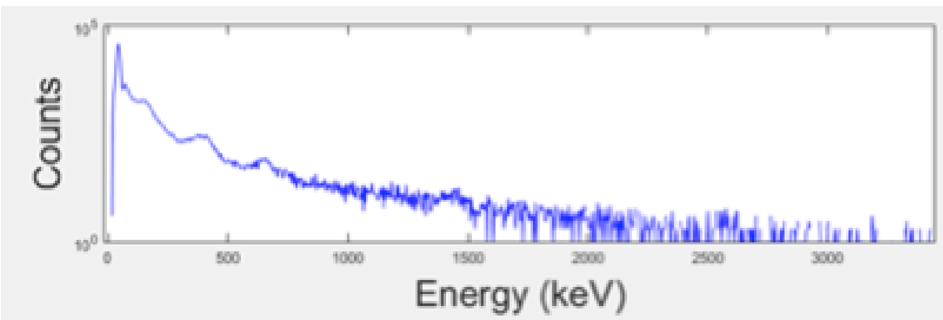


Thrust Area V subprograms

- Verification Using Inherently Trustworthy Instruments (Univ. of Michigan)
  - SAR ADC's with non-uniform bin resolution
  - Lead: David Wehe
  - Student: Fred Buhler
  - Collaborating with: **LLNL**
- Information Barriers with Enhanced Automated Isotope Identification (UIUC)
  - Lead: Clair Sullivan
  - Student: Mara Watson,
  - Collaborating with: **DAF**
- Zero Knowledge template verification (Princeton + Yale)
  - neutron radiography → comparison to a template
  - Leads: Alex Glaser, Francesco d'Errico, Robert Goldston.
  - Student: Sebastian Philippe
  - Collaborating with: **PPPL, DAF**
- Physical Cryptographic Verification of Nuclear Warheads (MIT)
  - transmission NRF to produce a physical hash of a nuclear warhead → comparison to a template
  - Leads: Richard Lanza, Areg Danagoulian, Scott Kemp
  - Students: Jayson Vavrek, Ruaridh Macdonald, Ellie Immerman, Amelia Turner, Jake Hecla
  - Collaborating with: **PNNL**

Information Barriers with Enhanced Automated Isotope Identification (UIUC)

- Given allowable peaks to be measured:
  - Enhanced automated isotope identification algorithms for improved information security
  - Accurate identification with different detectors
- Results:



<u>Identifications with > 50% posterior probability:</u>
Pu-239: 84.7%
Am-241: 84.1%
Pu-239 + Am-241: 57.7%

Spectrum of BeRP ball + 4 cm polyethylene + 1.27 cm Pb, collected with 2x2 in. NaI in 2 minutes

Wavelet Analysis and Derivation of Peak Areas

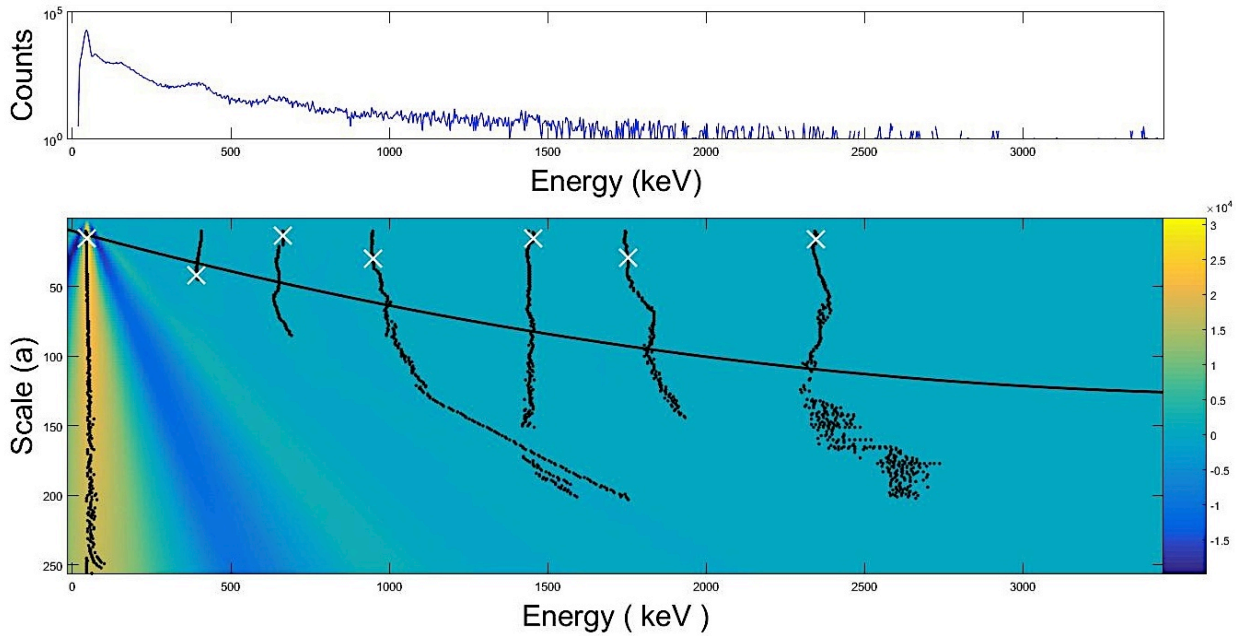
Step 1: Calculate wavelet transform

$$WX = S$$

$$S(a,E) = \int_{-\infty}^{\infty} X(t) \cdot \frac{1}{\sqrt{a}} \psi^*\left(\frac{t-E}{a}\right) dt$$

$$
\begin{aligned}
S &: = \text{CWT coefficient matrix} \\
W &: = \text{Wavelet transform tensor} \\
X &: = \text{Spectrum vector} \\
E &: = \text{Wavelet centroid parameter} \\
a &: = \text{Wavelet scale parameter} \\
B &: = \text{Wavelet basis matrix} \\
B_1 &: = \text{Optimal submatrix of B} \\
k &: = \text{Fit vector, wavelet representation of X} \\
C_S &: = \text{Signal covariance} \\
C_k &: = \text{Fit covariance}
\end{aligned}
$$

Step 2: Determine WTMM lines, filter, and find maxima along lines



Peak centroids, areas, uncertainties provided to Bayesian ID code

- Sample identifications made from DAF and LANL measurements
- All spectra collected with NaI, 60 second integration time
- Red indicates incorrect identification

Source	Shielding	Amount	Distance (cm)	ID
Se-75		0.54 mCi	50	Se-75, Eu-152
Eu152		10 uCi	30	Eu-152
Eu152 / Ba-133		10 uCi / 0.4 uCi	10 / 2	Eu-152
U-233		1 g	100	U233, Th-232
HEU (93.2% U-235)	1.2 cm Fe	13 kg	120	U-235
WGPu (BeRP Ball) (93.7% Pu-239)		4.5 kg	120	Pu-239, Am-241, I-125
WGPu (BeRP Ball) (93.7% Pu-239)	1.2 cm Pb	4.5 kg	120	Pu-239, Am-241

Thrust Area V subprograms

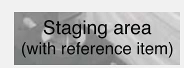
- **Verification Using Inherently Trustworthy Instruments (Univ. of Michigan)**
  - SAR ADC's with non-uniform bin resolution
  - Lead: David Wehe
  - Student: Fred Buhler
  - Collaborating with: **LLNL**
- **Information Barriers with Enhanced Automated Isotope Identification (UIUC)**
  - Lead: Clair Sullivan
  - Student: Mara Watson,
  - Collaborating with: **DAF**
- **Zero Knowledge template verification (Princeton + Yale)**
  - neutron radiography → comparison to a template
  - Leads: Alex Glaser, Francesco d'Errico, Robert Goldston.
  - Student: Sebastian Philippe
  - Collaborating with: **PPPL, DAF**
- **Physical Cryptographic Verification of Nuclear Warheads (MIT)**
  - transmission NRF to produce a physical hash of a nuclear warhead → comparison to a template
  - Leads: Richard Lanza, Areg Danagoulian, Scott Kemp
  - Students: Jayson Vavrek, Ruaridh Macdonald, Ellie Immerman, Amelia Turner, Jake Hecla
  - Collaborating with: **PNNL**

Zero Knowledge Warhead Verification with Neutron Transmission and Emission Measurements

Physical zero-knowledge object-comparison system at PPPL (*Nature Communications*, 2016): Expansion and demonstration of the Glaser, Barak, Goldston (GBG) Protocol (*Nature*, 2014)

- Use active neutron interrogation in a Zero Knowledge configuration:
    - transmission radiographs are recorded on detectors preloaded with the complement radiograph (including Poisson noise) of a reference item.
    - If the item is valid (identical to the reference), the final radiograph is identical to the expected exposure if no object had been present.

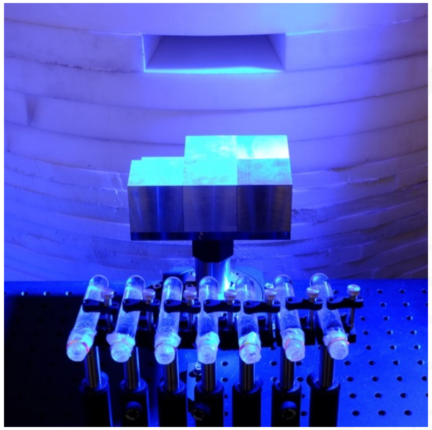
- Proof-of-concept system demonstrates fast neutron differential radiography can confirm that two objects have identical neutron opacity without revealing geometries/composition.



S. Philippe, R. J. Goldston, A. Glaser and F. d'Errico, "A physical zero-knowledge object-comparison system for nuclear warhead verification," *Nature Communications*, 7:12890 (2016), doi:10.1038/ncomms12890.

ZERO-KNOWLEDGE WARHEAD VERIFICATION

HIGHLIGHTS OF EXPERIMENTS



14-MEV OBJECT-COMPARISON SYSTEM @PPPL

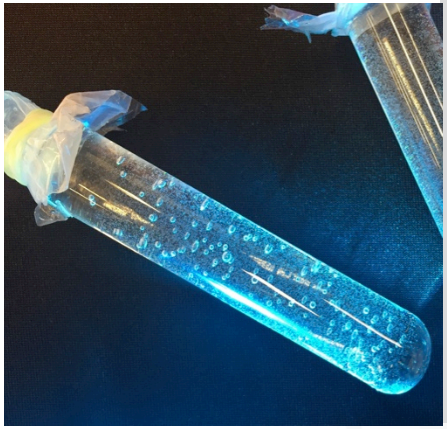
- 1st demonstration of a physical zero-knowledge proof
- Different configurations of 2′ ′ metal cubes
- Results show that when objects are identical, inspectors do not learn geometry or composition

ACTIVE INTERROGATION OF HEU @ DAF

- Transmission and emission measurements with different types of bubble detectors
- Two configurations of the Rocky Flats HEU shells
- Different sources with ~300-keV (AmLi), 2.5-MeV (DD) and 14-MeV (DT) neutrons

ZERO-KNOWLEDGE WARHEAD VERIFICATION

DETECTOR DEVELOPMENT (YALE)



<u>TRANSMISSION</u>

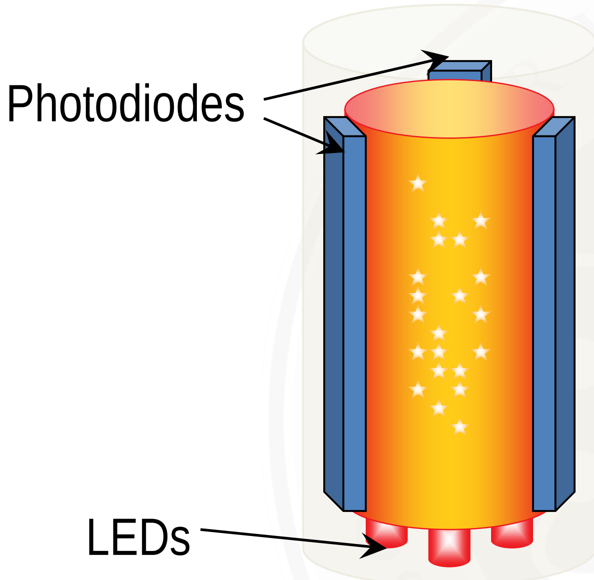
- Capable of storing > 1,000 counts
    - Preloads indistinguishable from measurement counts
- Insensitive to gamma radiation
- Sensitive to neutrons above selected thresholds
    - Some thresholds of interest: 3 and 10 MeV

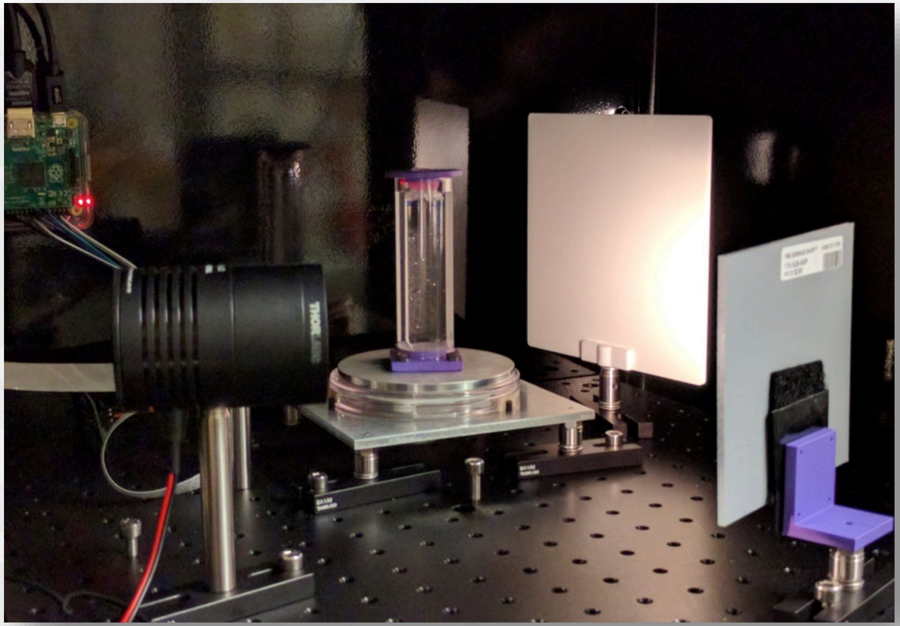
<u>EMISSION</u> (spontaneous and driven)

- **Capable of storing thousands of counts**
    - No imaging at present
- **Insensitive to gamma radiation**
- **Sensitive mainly to fission neutrons**
    - Energy threshold ~500 keV or above source

ZERO-KNOWLEDGE WARHEAD VERIFICATION

NEW READING TECHNIQUES (YALE + PRINCETON)





OPTOELECTRONIC READOUT (YALE)

- A beam of infra-red light crosses the active area of the detector and is deflected by evaporated bubbles.
- Photodiodes affixed along the detector length selectively detect the scattered light component post-irradiation.

360-OPTICAL TOMOGRAPH (PU)

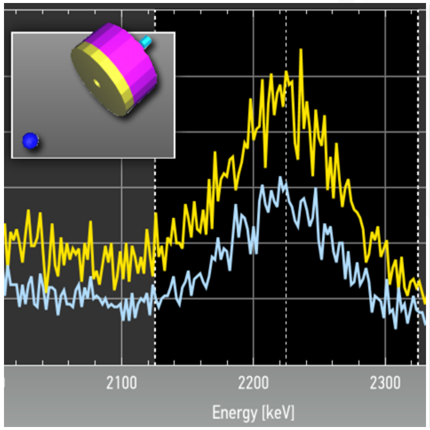
- Takes 360-degrees movies of detectors.
- Use PU open-source bubble counting software. (in development).
- To be upgraded with HeNe laser scattering for data commitment experiments.

OPEN SOURCE INFORMATION BARRIER

PASSIVE GAMMA AND NEUTRON

INFORMATION BARRIER EXPERIMENTAL (IBX)

- Open source software, towards open hardware
- Encourage others to improve or defeat IBX
- Successfully tested at DAF



MULTI-CRITERIA-TEMPLATE APPROACH

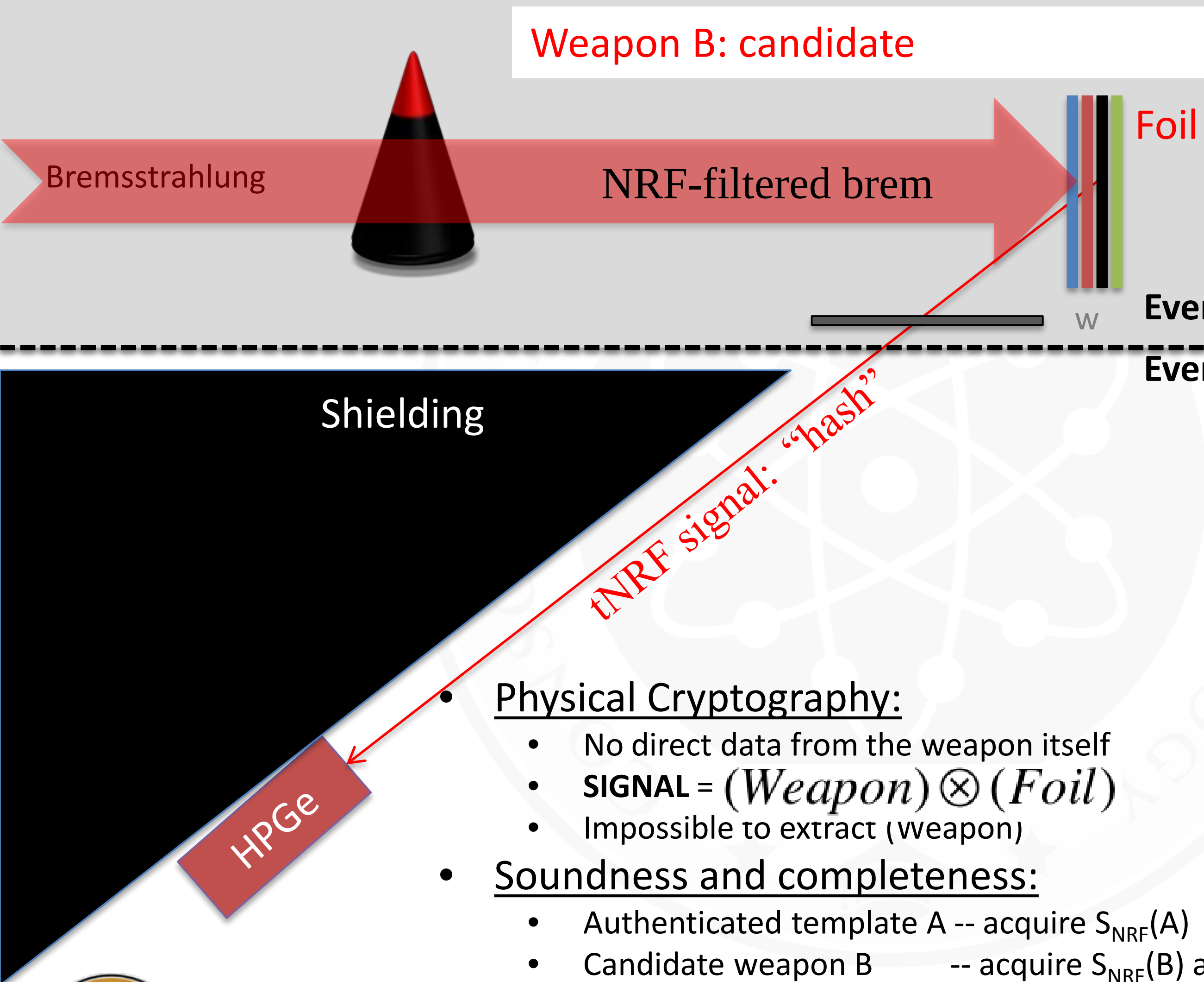
- Compares gamma spectrum and count rate
- Compares neutrons indirectly through 2223 keV gammas from polyethylene → sensible to mass
- Implemented in IBX

M. Göttsche, J. Schirm, and A. Glaser. "Low-resolution Gamma-ray Spectrometry for an Information Barrier Based on a Multi-Criteria Template-Matching Approach." *Nuclear Instruments and Methods in Physics Research Section A* (2016).

Thrust Area V subprograms

- Verification Using Inherently Trustworthy Instruments (Univ. of Michigan)
  - SAR ADC's with non-uniform bin resolution
  - Lead: David Wehe
  - Student: Fred Buhler
  - Collaborating with: **LLNL**
- Information Barriers with Enhanced Automated Isotope Identification (UIUC)
  - Lead: Clair Sullivan
  - Student: Mara Watson,
  - Collaborating with: **DAF**
- Zero Knowledge template verification (Princeton + Yale)
  - neutron radiography → comparison to a template
  - Leads: Alex Glaser, Francesco d'Errico, Robert Goldston.
  - Student: Sebastian Philippe
  - Collaborating with: PPPL, DAF
- Physical Cryptographic Verification of Nuclear Warheads (MIT)
  - transmission NRF to produce a physical hash of a nuclear warhead → comparison to a template
  - Leads: Areg Danagoulian, Scott Kemp, Richard Lanza
  - Postdoc: Brian Henderson
  - Students: Jayson Vavrek, Ruaridh Macdonald, Bobby Nelson, Jake Hecla
  - Collaborating with: **PNNL**

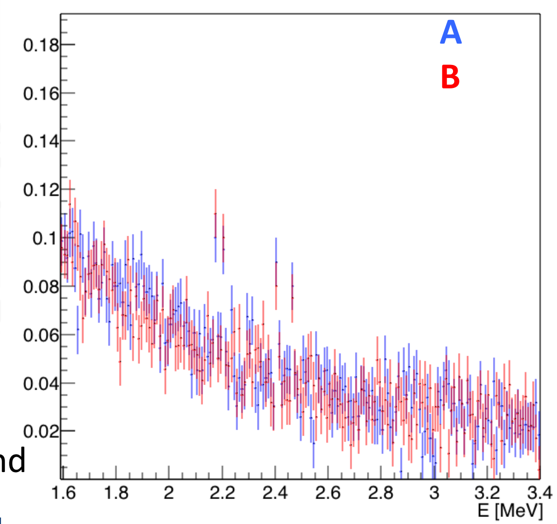
NRF Weapon authentication Concept



Everything classified by the host

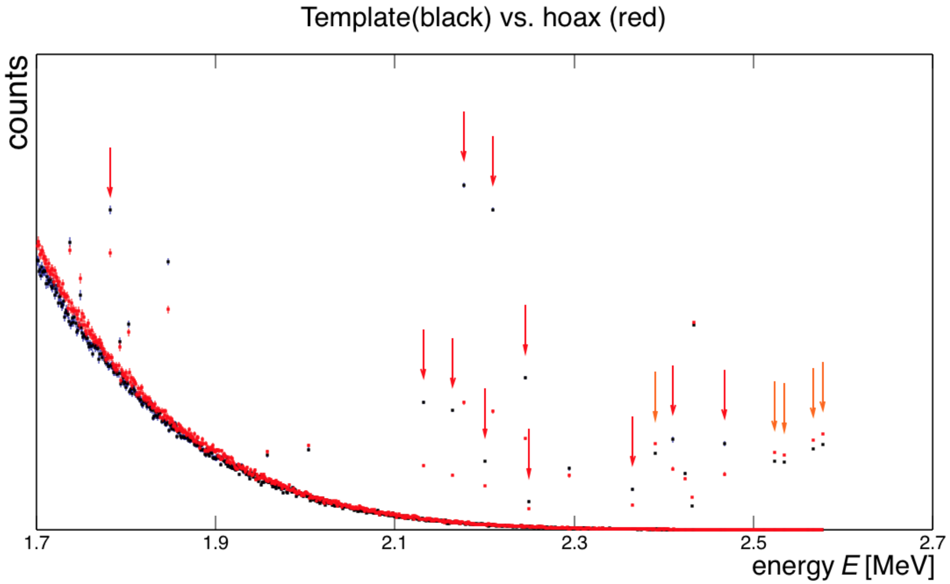
Everything open

- <u>Physical Cryptography:</u>
  - No direct data from the weapon itself
  - **SIGNAL** = $(Weapon) \otimes (Foil)$
  - Impossible to extract (weapon)
- <u>Soundness and completeness:</u>
  - Authenticated template A -- acquire $S_{NRF}(A)$
  - Candidate weapon B -- acquire $S_{NRF}(B)$ and compare



Verification Concept with transmission NRF

Geant4 Monte Carlo feasibility studies: template vs. various hoaxes
Example: WGP → DU replacement hoax



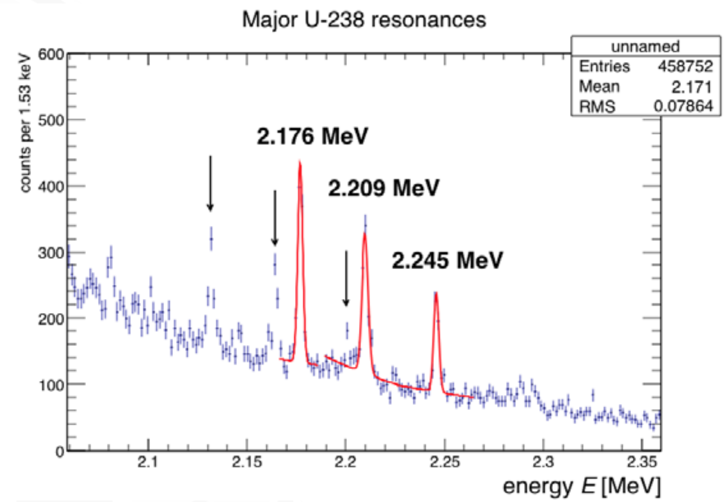
Hoax Scenario	Detection $\|n\| > 5\sigma$?
Template vs. Authentic	—
Template vs. WgPu → ^{238}U	yes
Template vs. WgPu → FgPu	yes
Template vs. Geometric Hoax oriented to be undetectable	no (by design)
Template vs. Geometric Hoax after 10° rotation	yes

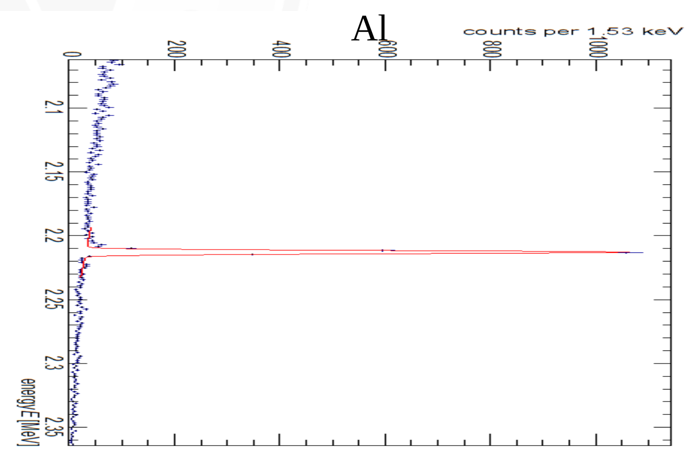
→ can catch most hoaxes within minutes

- R.S. Kemp, A. Danagoulian, R.R. Macdonald, J.R. Vavrek, "**Physical Cryptographic Verification of Nuclear Warheads**," Proceedings of the National Academy of Sciences, vol. 113 no. 31 (2016)

Verification Concept with transmission NRF

- Preliminary results:
  - 238U – observed all the primary and secondary resonances
  - Al – acquired data for normalization to 27Al's known cross section



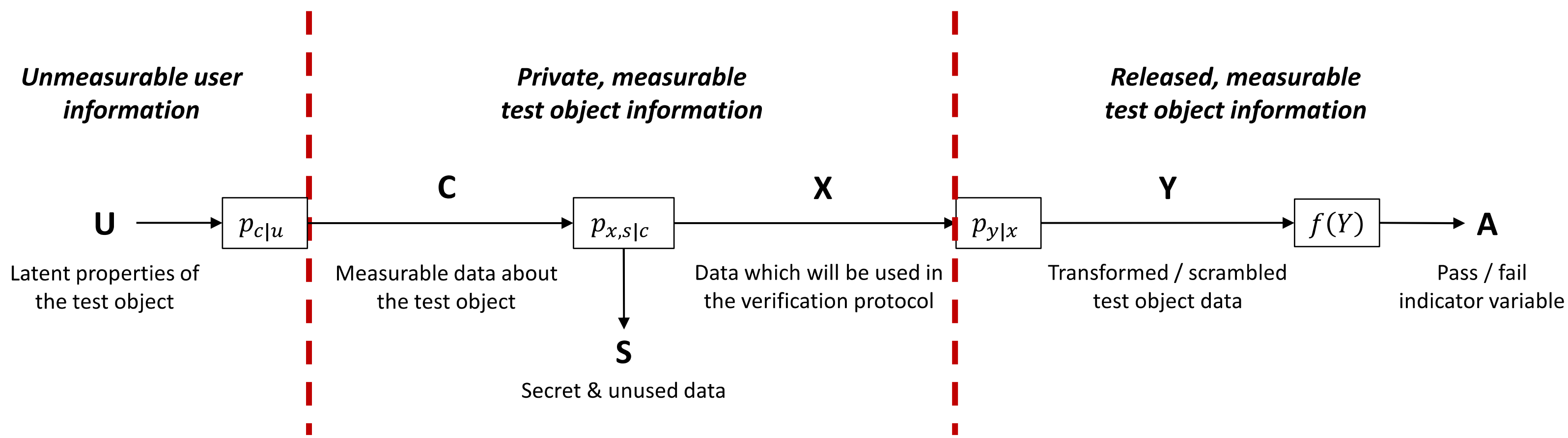


- Students and postdocs
  - Jayson Vavrek
  - Ruaridh Macdonald
  - Dr. Brian Henderson (Stanton postdoctoral fellow)
- Collaboration with Ken Jarman, PNNL, on the information theory problem

General framework for comparing warhead verification protocols

- Quantify how each step of the protocol effects completeness/soundness/secrecy
- Methods developed from techniques in problems of data privacy

$p_{c\|u}$	Axiom linking latent properties (e.g. 'warheadness') and measurable data
$p_{x,s\|c}$	Function which extracts the data which host and investigator agree is necessary to identify a warhead via attributes or template
$p_{y\|x}$	Function describing the process by which the released data is obfuscated to protect warhead secrets
$f(Y)$	Function describing the verification protocol



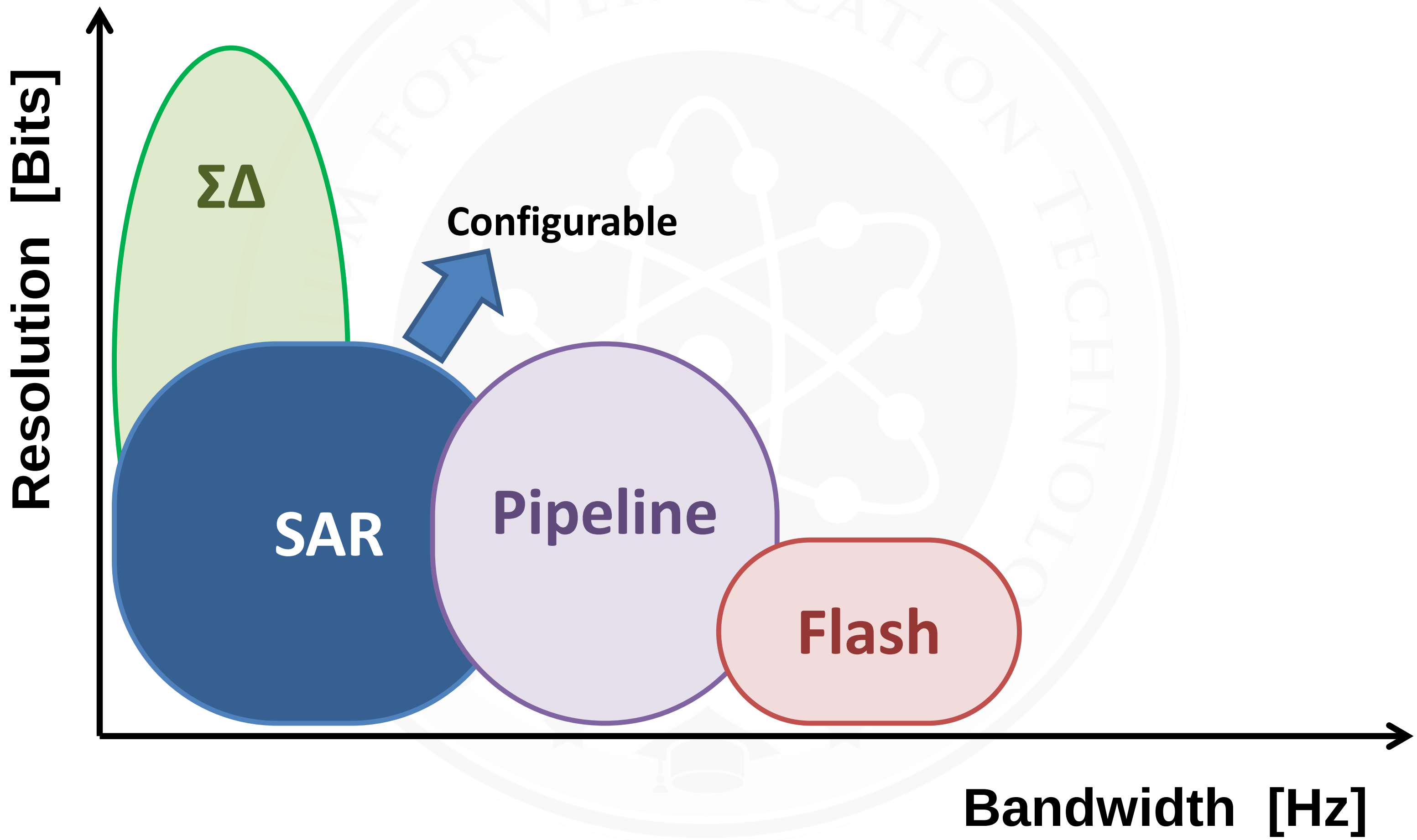
Conclusion

- Solid progress on all projects:
  - experimental proof of concept demonstration of neutron radiography verification protocol (Princeton)
  - optimized neutron bubble detectors for Zero Knowledge neutron radiography (Yale)
  - completed feasibility simulations of the Nuclear Resonance Fluorescence (NRF) protocol, taking experimental data (MIT)
  - analyzed data from Device Assembly Facility (DAF) for spectral algorithm development (Illinois)
  - Developing a new, non-uniform ADC concept for gamma spectroscopy (UM)

BACKUP

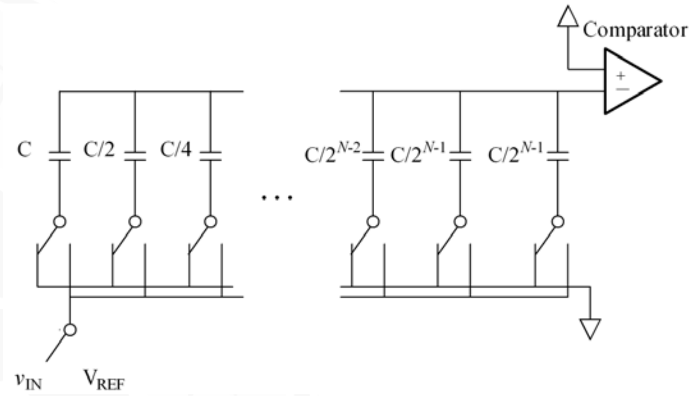
Understanding the problem

Fundamental Analog to Digital Converters (ADCs)

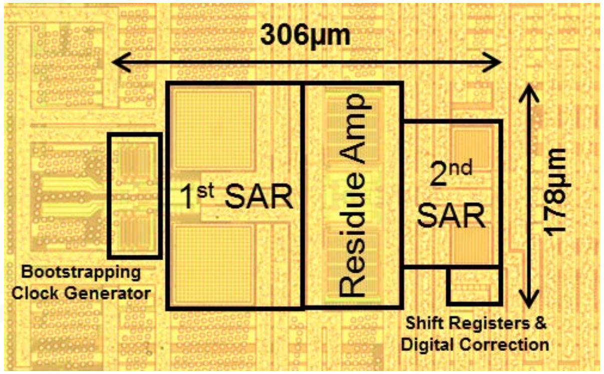


Moving Forward

- Exploits existing R&D for consumer appliances.
- State of the art, published in ISSCC 2015
- SAR ADC with 50 Msps, 11.5 ENOB, 1mW, in CMOS
- 2-stage ADCs are common approach.
- Newly proposed architecture implementable with modifications to residue amp and 1st SAR capacitor DAC
- Modify the current design to fabricate and test a candidate treaty-acceptable inspection system
- HPGe measurement system assembled.
- Interfaces with national lab, industrial partners during design phase.



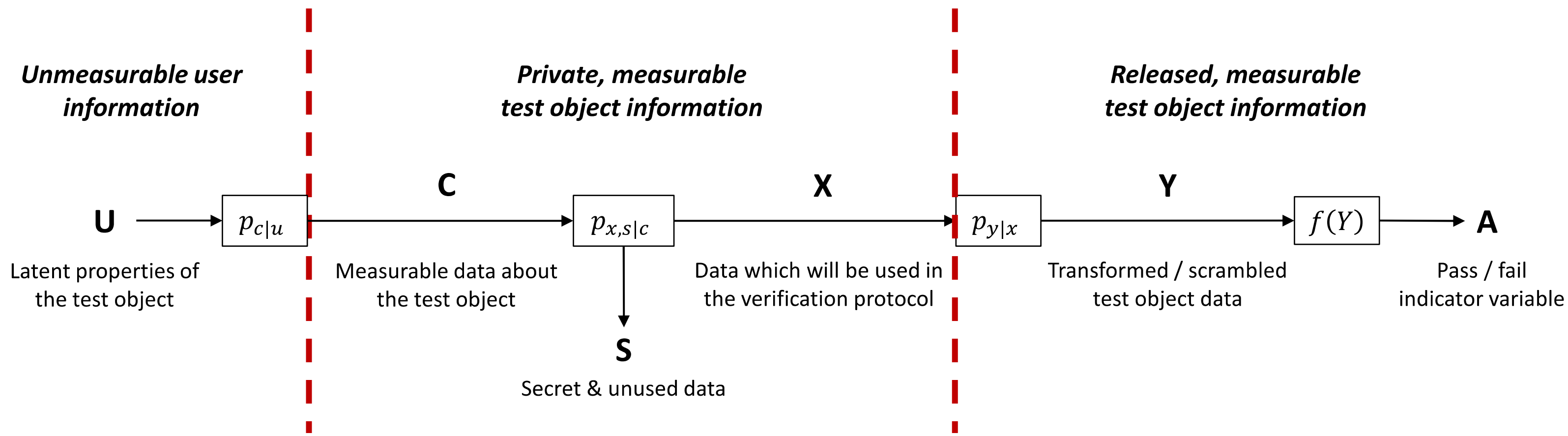
Charge Redistribution Successive Approximation ADC



Silicon Implementation

We are developing a general framework for comparing warhead verification approaches

- Protocol steps are described by mathematical functions
  - All one-to-one / many-to-one relationships are made explicit
- Various measures of mutual information are used to quantify how much information about the test object / warhead is passed on at each protocol step
  - This quantifies the information the inspector receives, i.e. the completeness and soundness
  - The warhead owner can calculate the protocol secrecy using the mutual information between the measured data and the warhead design → this is agnostic to inference method

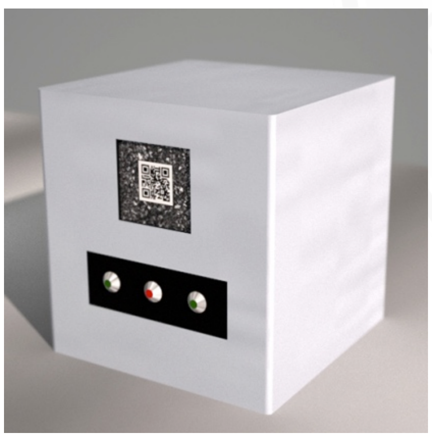


MINIMALLY-INTRUSIVE VERIFICATION

NUMERICAL LIMITS ON WARHEADS WITH "BUDDY TAG"

WARHEAD COUNTING

- The challenge: establish a baseline count of warheads and enforce a ban on un-tagged items in a variety of operational environments.
- Numerical counts of items must be trustable and the information security concerns of inspected parties must be respected.



BUDDY TAG CONCEPT

- Buddy tag acts as a companion token, proving ownership of a treaty-accountable item while remaining physically detached from the item itself.
- Declarations are verified by short notice inspections which confirm that all items are associated with a companion tag.

Images courtesy of Jose Lopez http://www.defenseimagery.mil (T), Tamara Patton (B)

[Book of the Dead - Wikipedia]

Flash ADC as example

- design with variable width comparators by adjusting the resistive ladders at the chip level.
- do this in CMOS technology to be cost effective.
- Key idea is to get superb energy resolution in regions of interest while blocking design information from scrutiny.
- Snag: Available flash ADCs do not have sufficient bit resolution. Need 10^3-10^4 matched comparators.