Integration of Sensing & Processing

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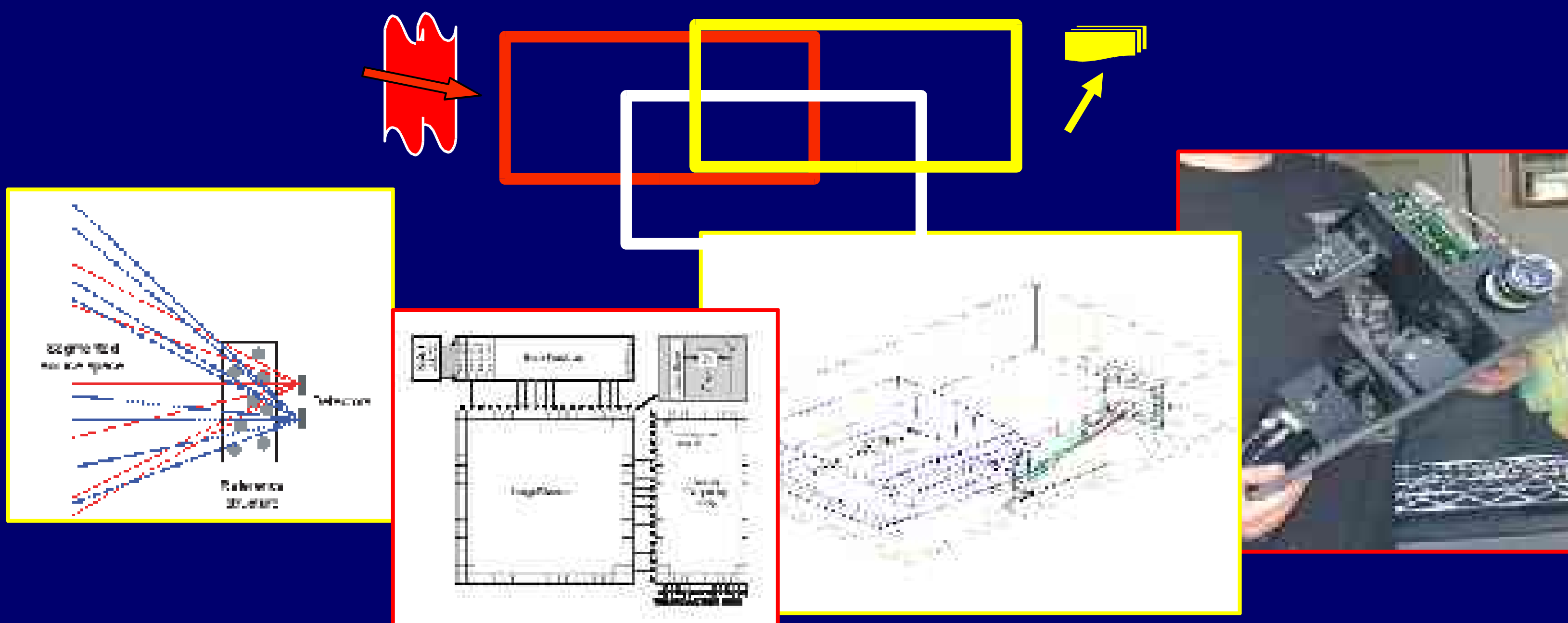

Outline

1. Introduction
   - Traditional sensing system design and operation
   - The integrated sensing & processing vision
2. Closing the sensing loop
   - Issues and approaches
   - Experiment sequence for target classification
   - Waveform scheduling
   - Coded-aperture sensors
3. Processing on the physical layer
   - Analogue-to-Information conversion
   - Optical reference structure devices
   - Combined analog-digital signal processing

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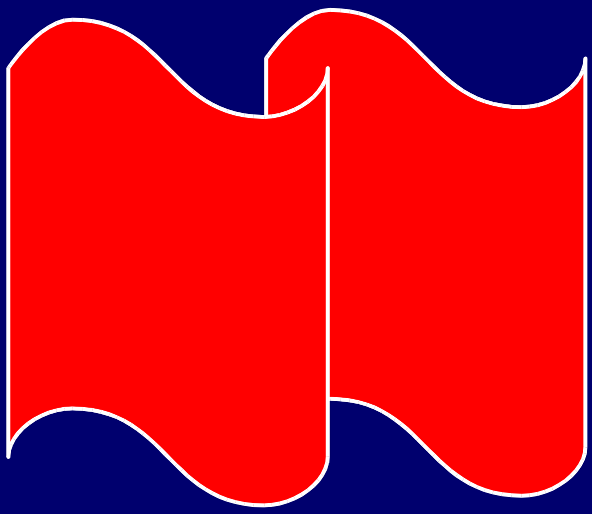
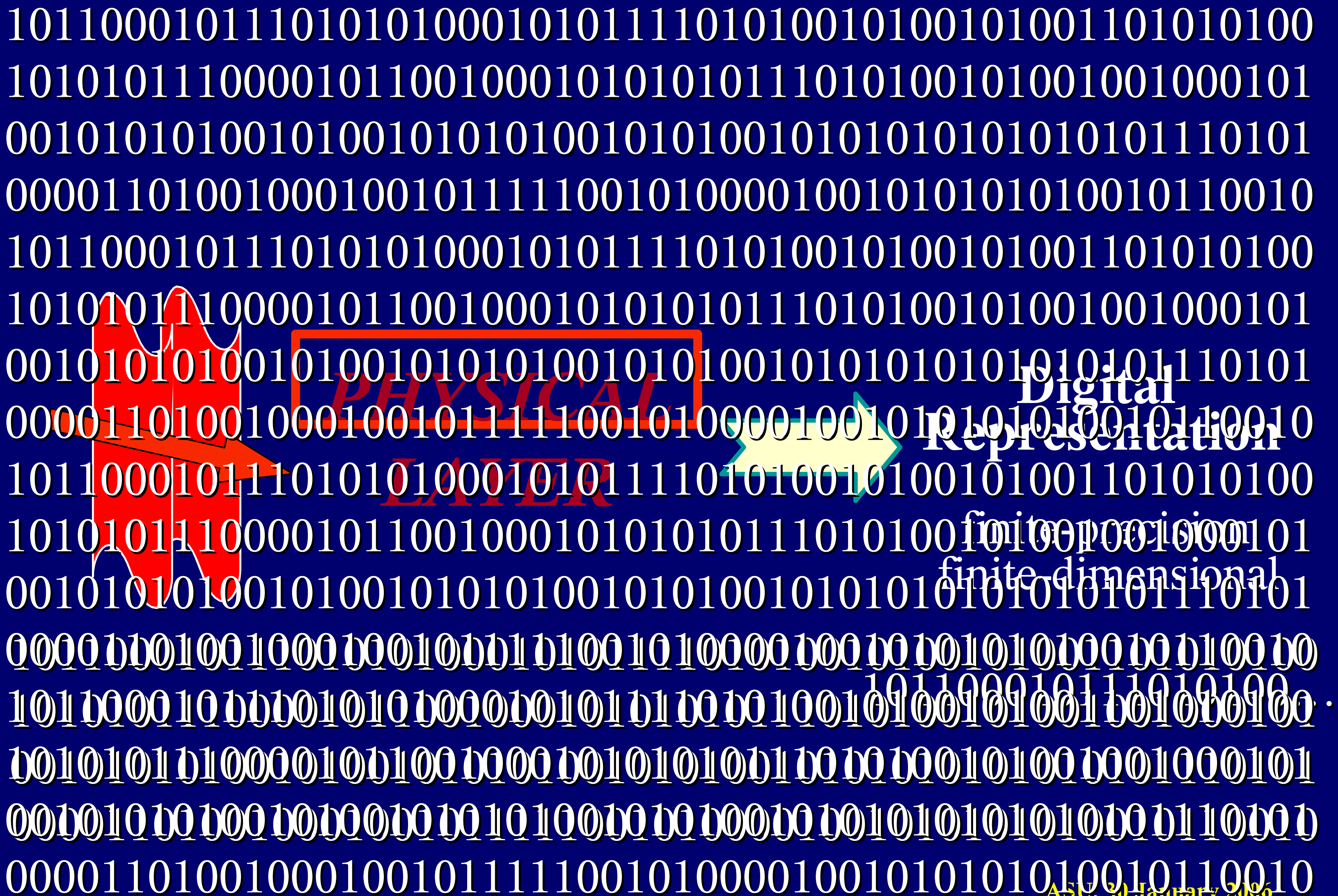
Traditional Sensing

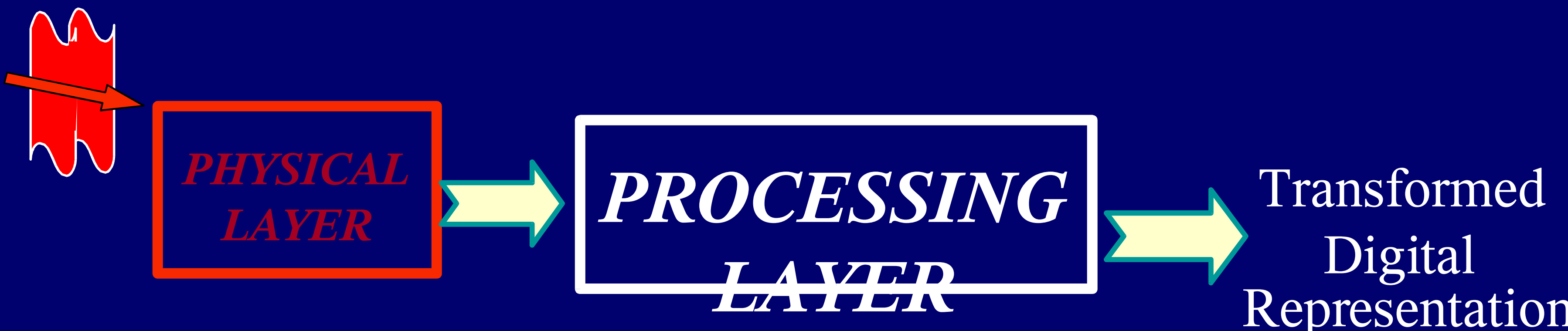
Physical
Phenomenology



Traditional Sensing



Traditional Sensing



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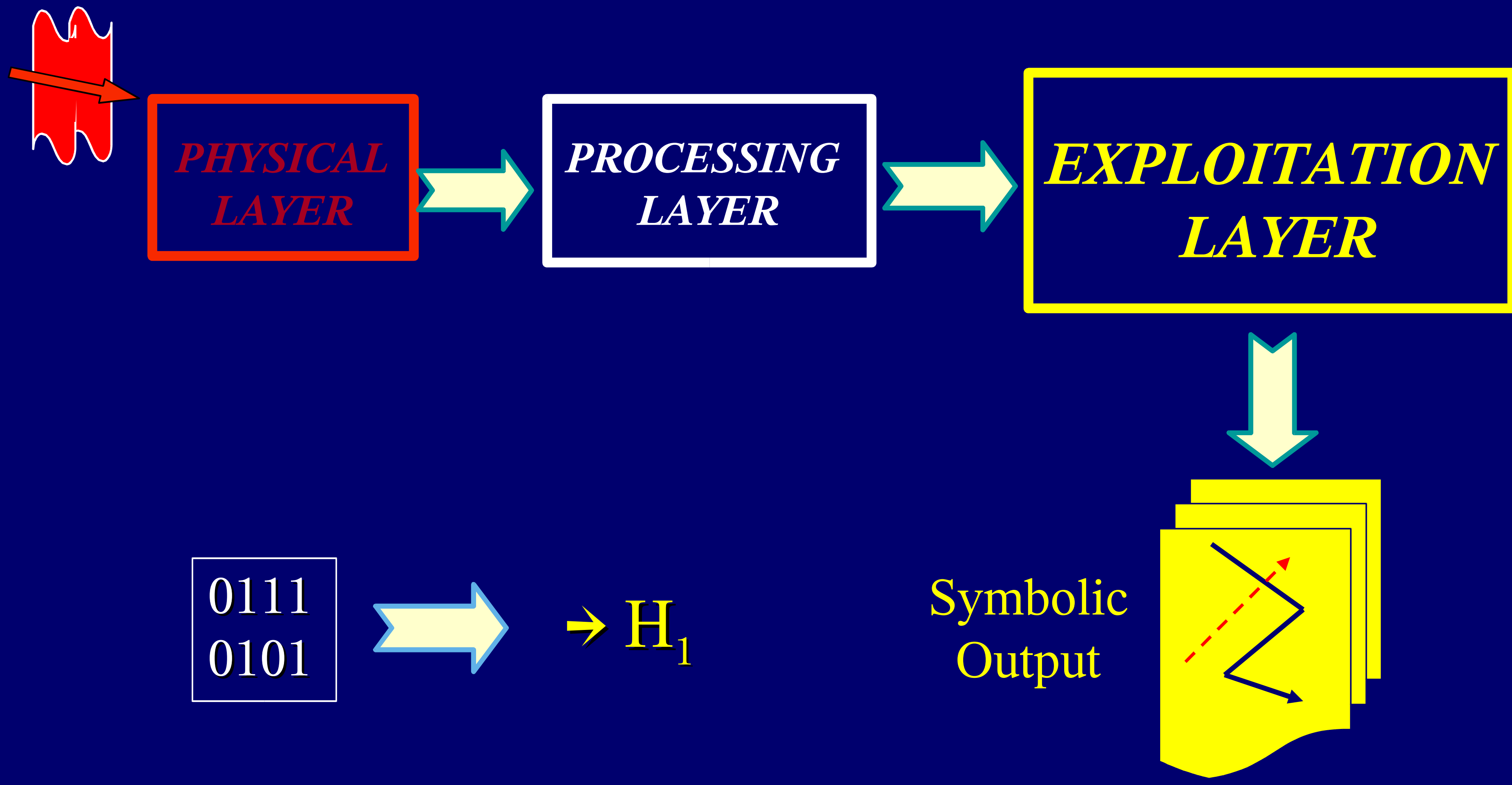
Traditional Sensing



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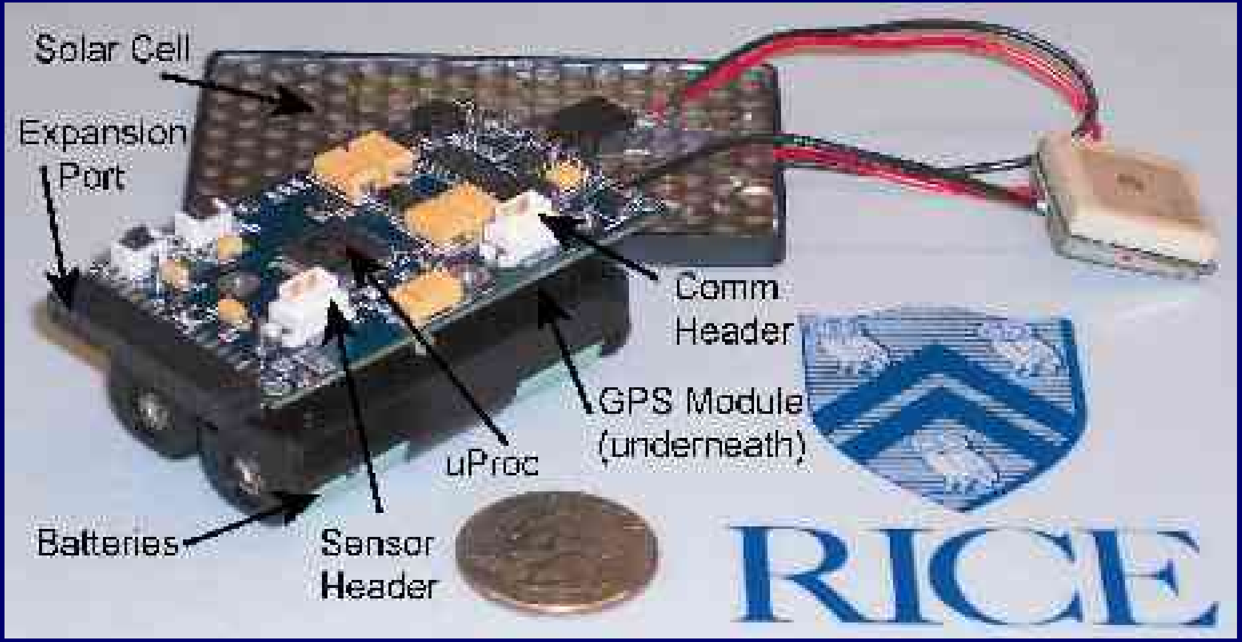
Integrated Sensing & Processing Vision

Agile sensing opportunities

- Optical: e.g., high-speed spatial light modulators, femtosecond pulse-shaped lasers
- RF: e.g., software-driven transmitters & receivers
- Acoustic: e.g., steerable & waveform-agile sources



- Configurable networks: e.g., deployable motes, unmanned vehicles
- Tunable materials: e.g., electrically tunable materials, photonic band-gap materials
- Chemical: e.g., artificial dogs' noses

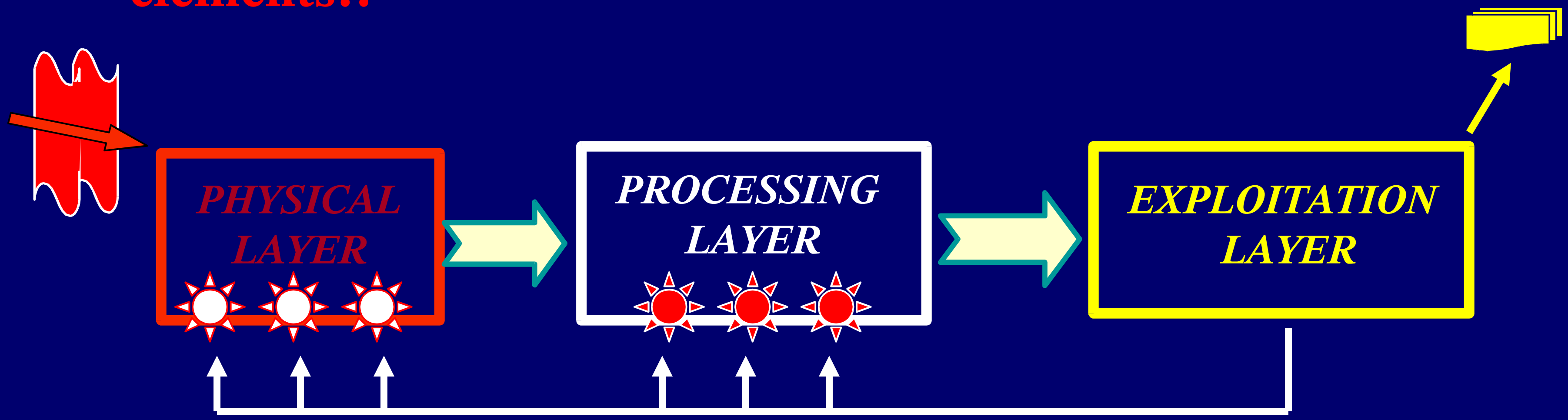
Integrated Sensing & Processing Vision

Hsiao Zhua-Zi
"Beast"
1984-2004

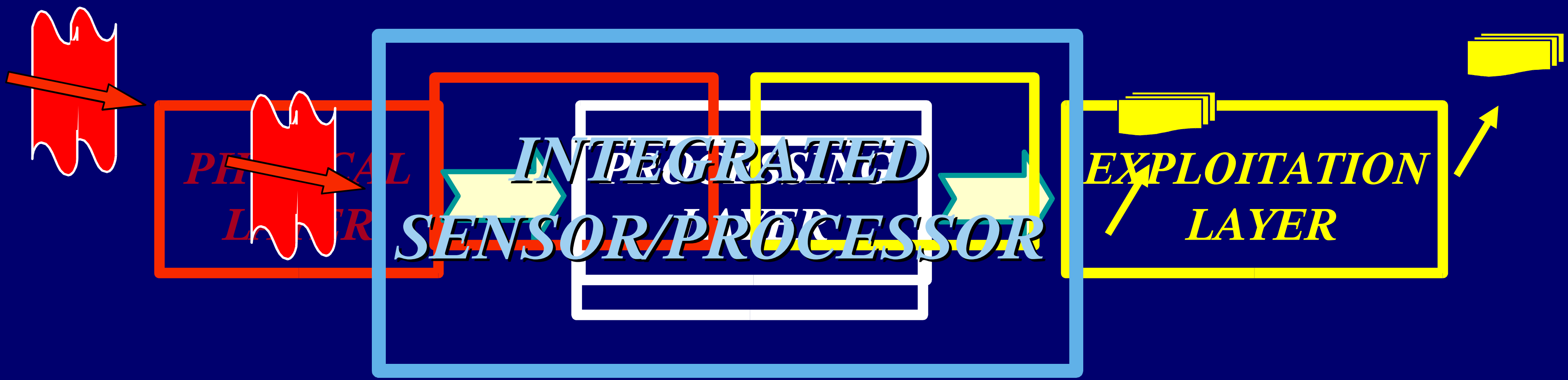
Integrated Sensing & Processing Vision

Develop holistic approaches to sensor system <u>design</u> and <u>operation</u> to enable optimal end-to-end performance

1) **Supplant currently prevalent feed-forward operational concepts with feedback ideas ➔ Allow back-end exploitation requirements (e.g., target ID) to task front-end sensor elements!!**



Integrated Sensing & Processing Vision



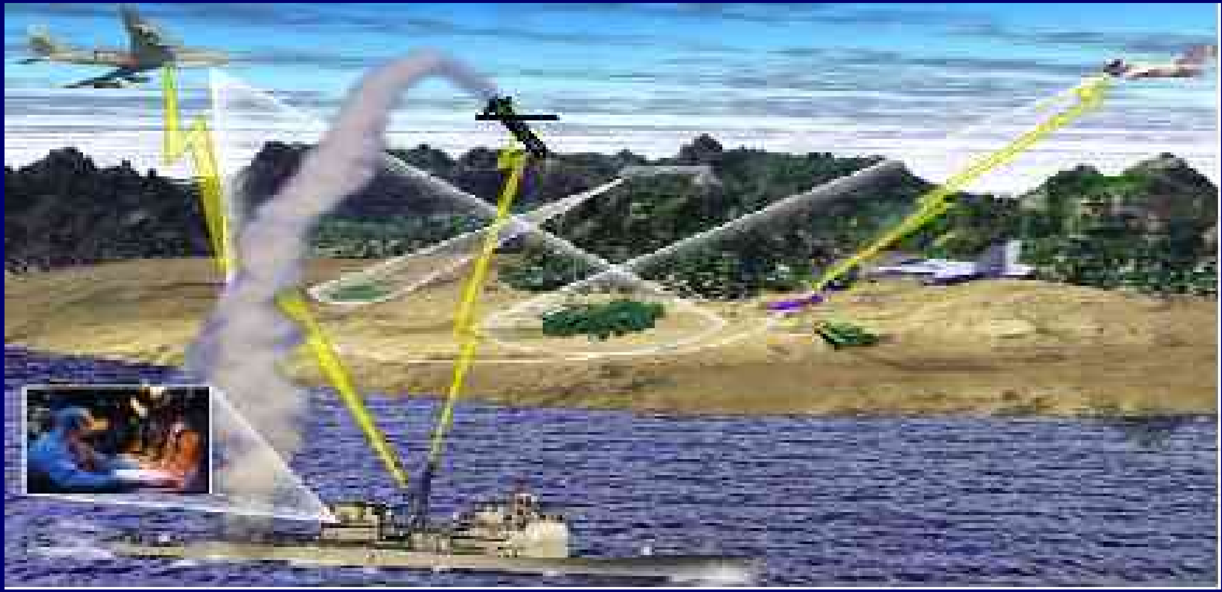
Develop holistic approaches to sensor system design and operation to enable optimal end-to-end performance

1) **Replace independent optimization of sensor system components with end-to-end system optimization ➔ Integrate processing and sensing functionality; e.g., “processing on the physical layer”**

DARPA ISP Program

Defense and national security sensing systems supporting next-generation reconnaissance, surveillance, and weapon capabilities face dramatically increased demands:

- Complexity and volume of raw measurements
- Increased operational tempo
- Concepts of operation with immediate information sharing
- More flexible (tunable, mode/waveform selectable, configurable, etc.) sensor elements



Raytheon

ISP is developing critical enabling methodology for the next generation of sensor/exploitation networks

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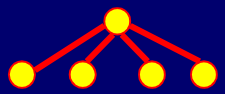
Closing the Loop: Issues

Myopic Perspective: ***Get the most out of <u>the next</u> measurement***

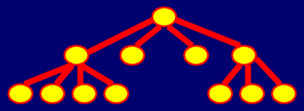


- **The most what?**
  - **Requires quantification of exploitation objectives**
- **Even single-step propagation of conditional densities is problematic**
  - **Non-linear**
  - **Non-Gaussian**

Finite Horizon Perspectives

Know as much as possible at some fixed future time

Reach a desired confidence level as quickly as possible



- **Myopic issues still apply**
- **Combinatorics quickly get out of hand**

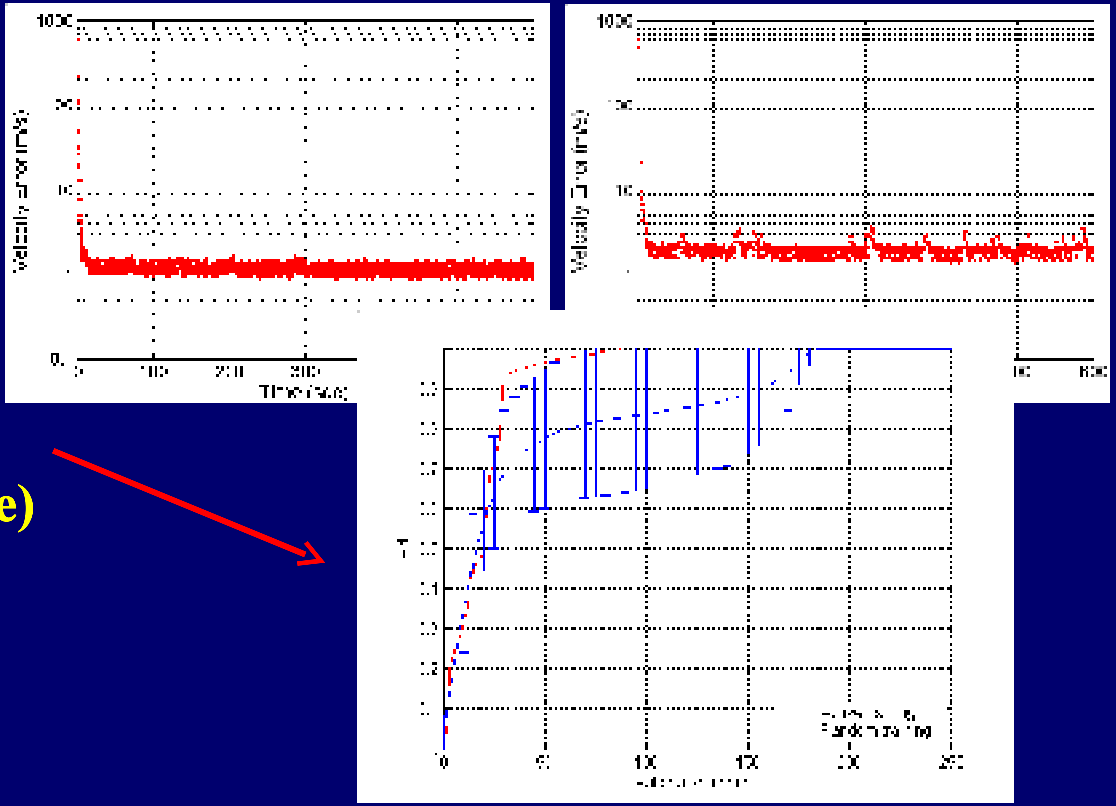
Closing the Loop: Approaches

Bayesian Analysis / Embedded Simulation

- Particle filtering propagates arbitrary quantized conditional densities through nonlinear systems
- But it can be slow – particularly in multi-stage problems

Testbed applications:

- Radar beam dwell management (MIT Lincoln Lab, General Dynamics)
- Waveform scheduling (Melbourne, DSTO)
- UXO and mine search (Duke)
- Chemical sensing (JHU)

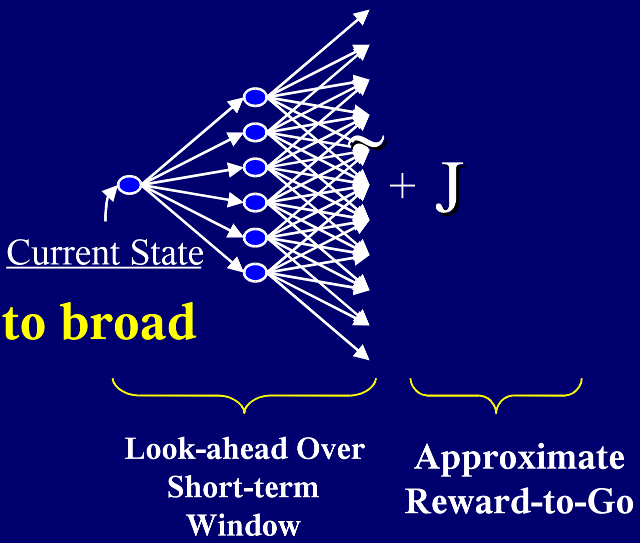


Closing the Loop: Approaches

Multi-armed Bandit Formulation

- Gittens index provides multi-stage solution
- Computing the index has traditionally been intractable
  except for small problems

Optimal Control Perspective
(Stochastic Dynamic Programming)



- Rich theory provides exact optimal solutions to broad classes of sensor scheduling problems
- Optimal solutions typically require extensive memory and communication

Testbed applications

- Multi-stage waveform scheduling (Melbourne University, DSTO, CSU)
- Radar dwell and mode management (Alphatech, Boston University, NRL)
- NMR probing of macromolecules (Harvard)

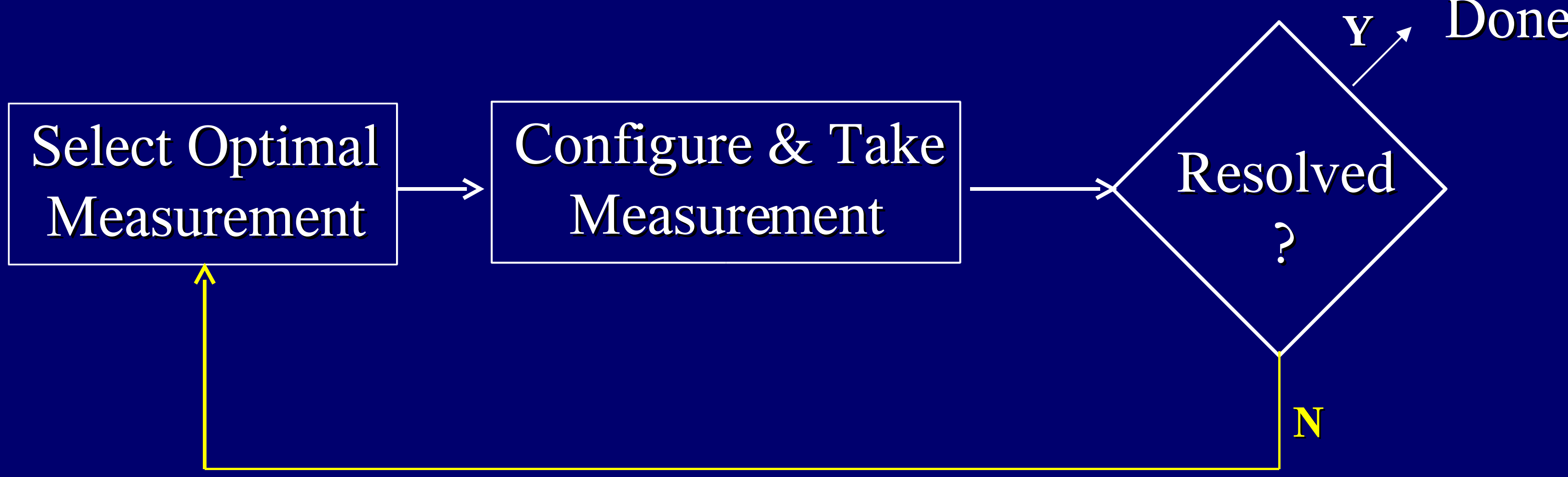
Closing the Loop: Examples

Design of experiment sequence for target classification

Measurement 1

Measurement 2

Measurement N

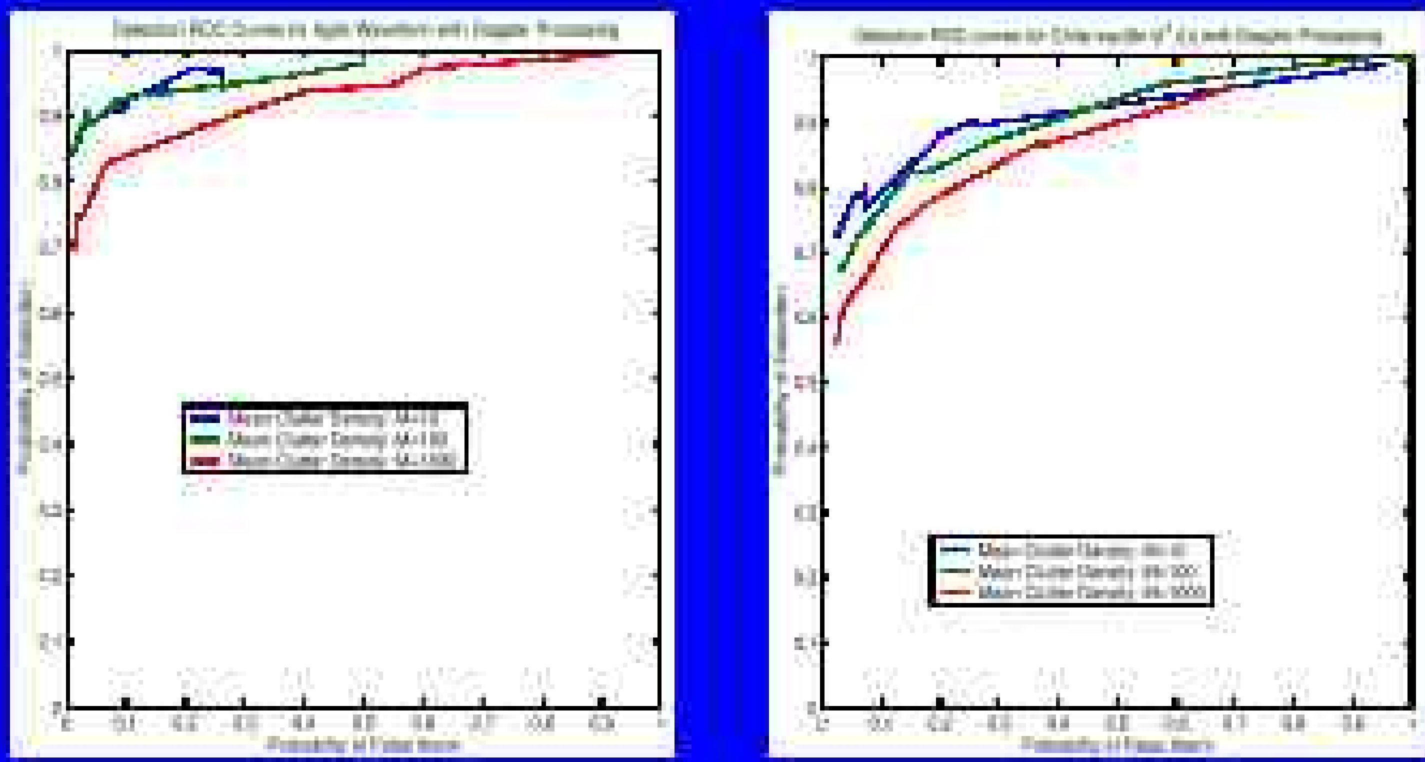


Closing the Loop: Examples

Classification Movie

Closing the Loop: Examples

Myopic Waveform Scheduling: Performance value
University of Melbourne, DSTO



(a) Using Waveform Agility

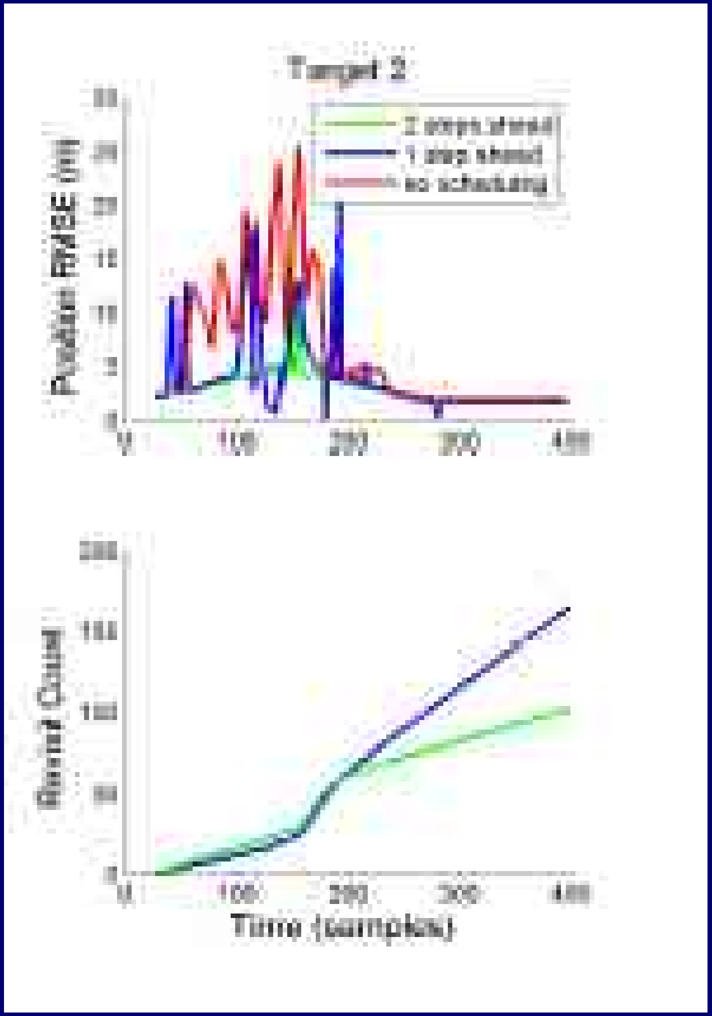
(b) Using LFM $s(t) = e^{8\pi i(t^2+t)}$

Closing the Loop: Examples

Non-myopic Waveform Scheduling: Performance value Melbourne, DSTO

Two steps ahead vs. one step ahead waveform scheduling in target tracking example

1. Position RMSE as a function of time
2. Re-visit count as a function of time

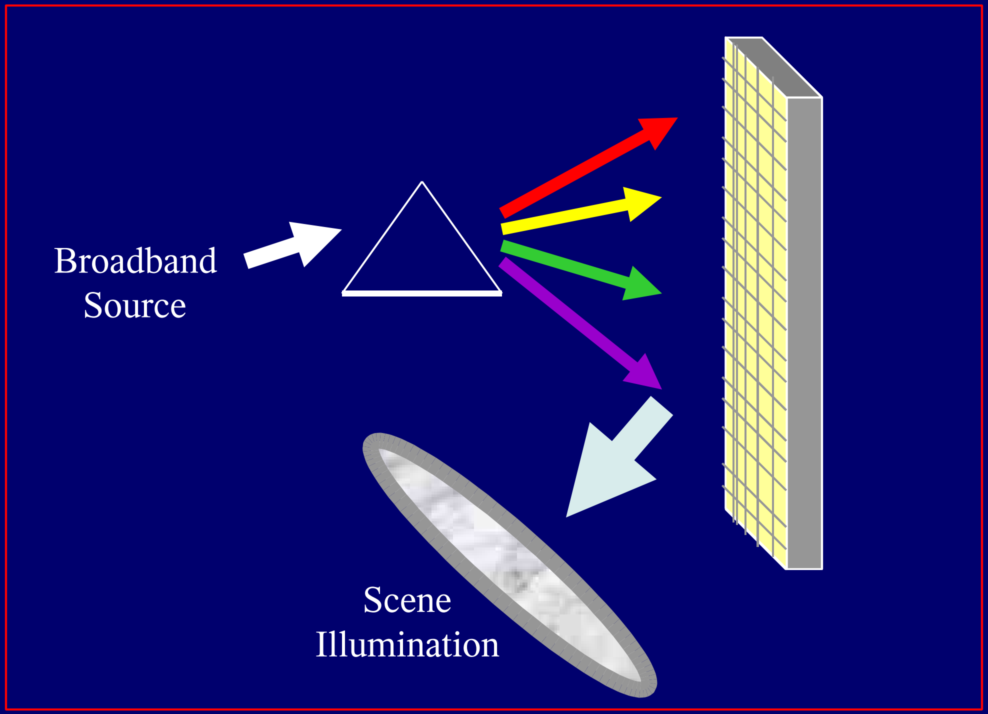


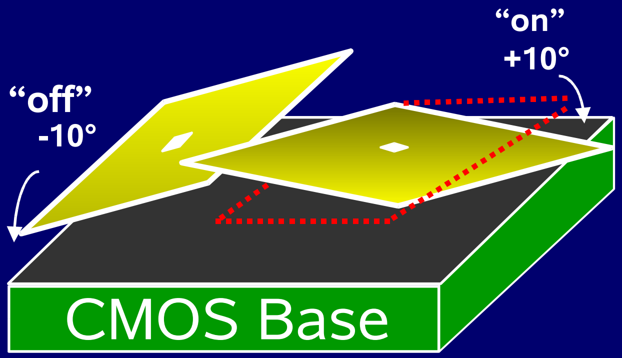
Can we develop rigorously-based heuristics for when multi-stage processing is worth the cost?

Closing the Loop: Examples

Coded-Aperture Sensing Devices
Yale University & FMAH Inc.

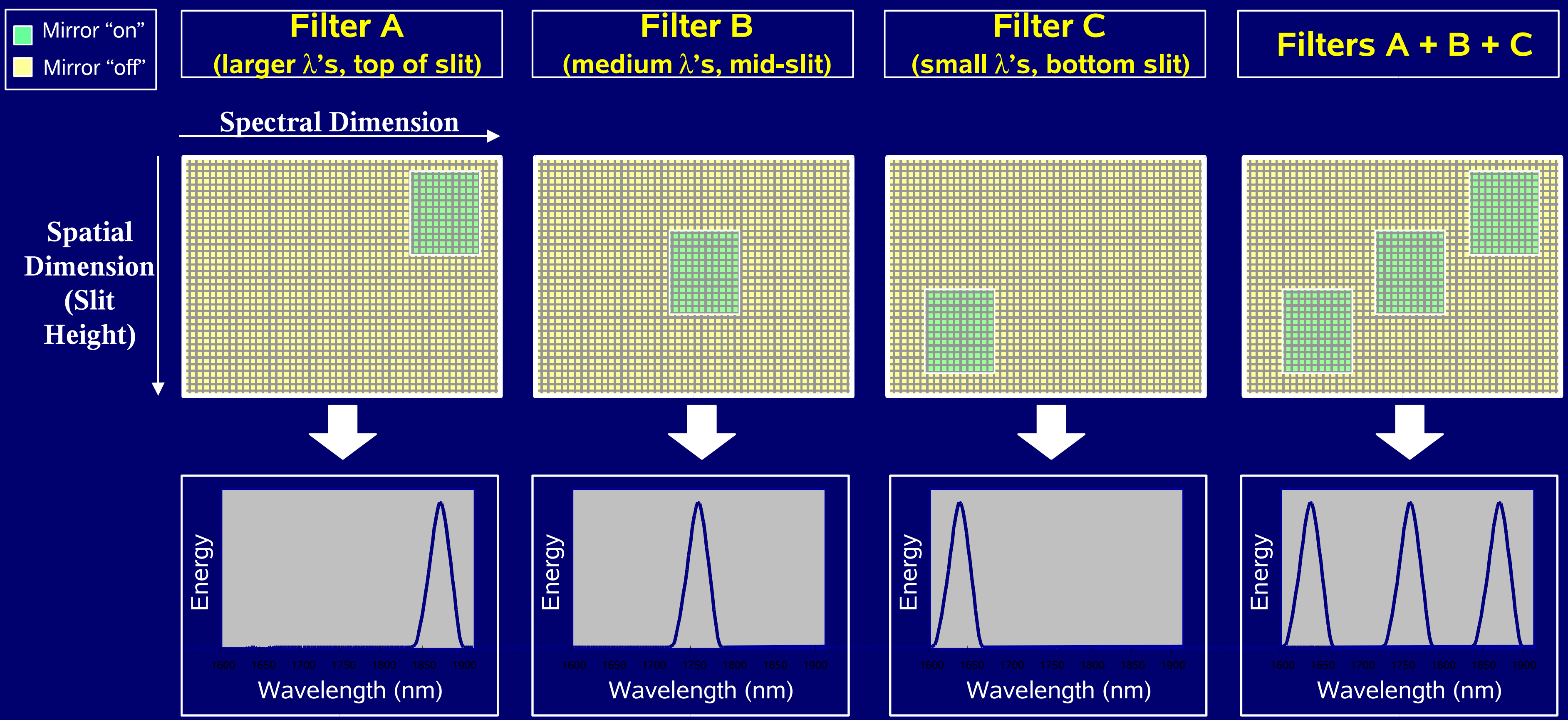
- **Digitally controlled light source used as a spectrometer or direct chemometric analysis system**
- **Algorithmically optimizing the illumination spectrum allows discrimination of materials**





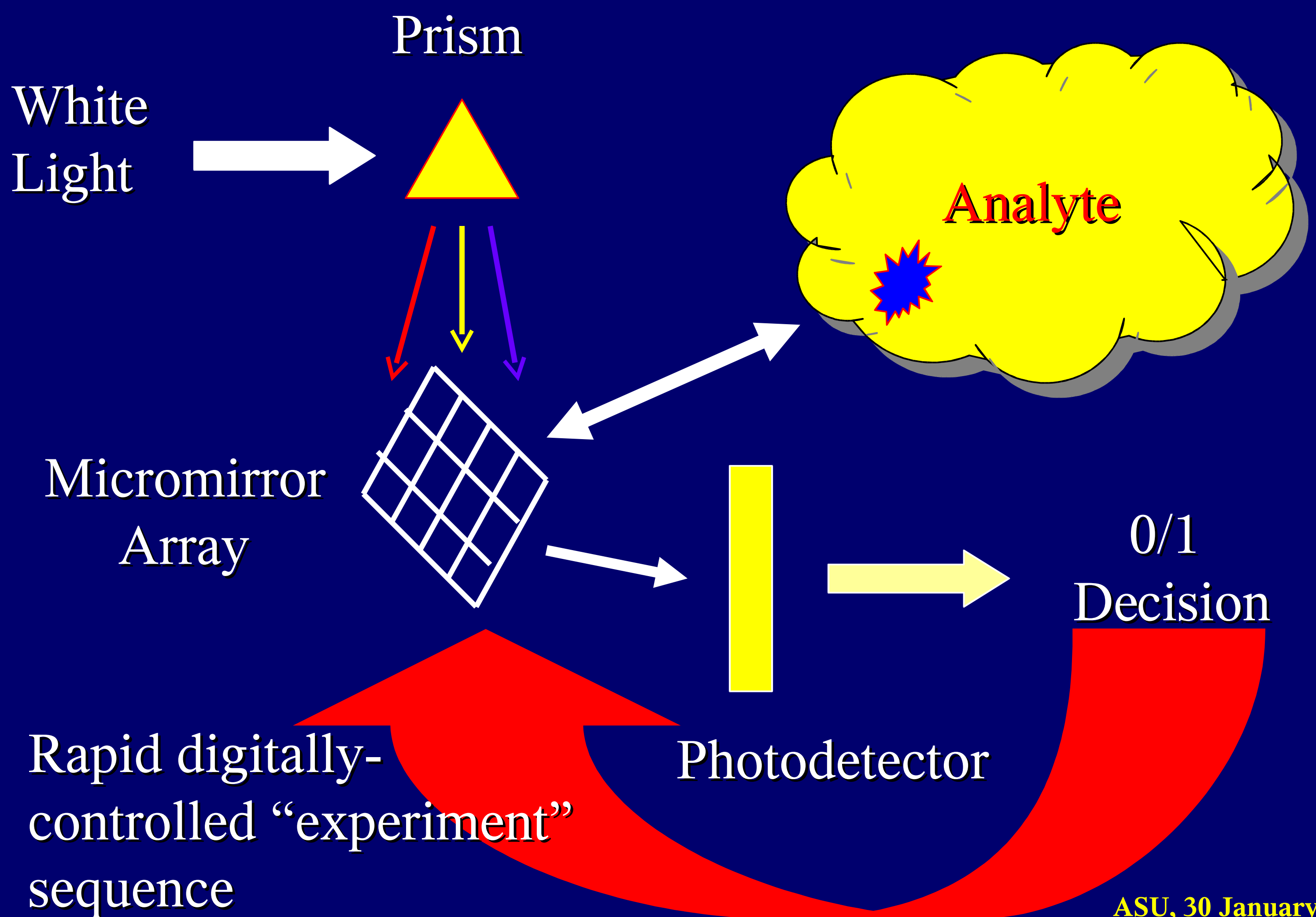
Closing the Loop: Examples

Spatio-spectral filtering with coded-aperture sensor



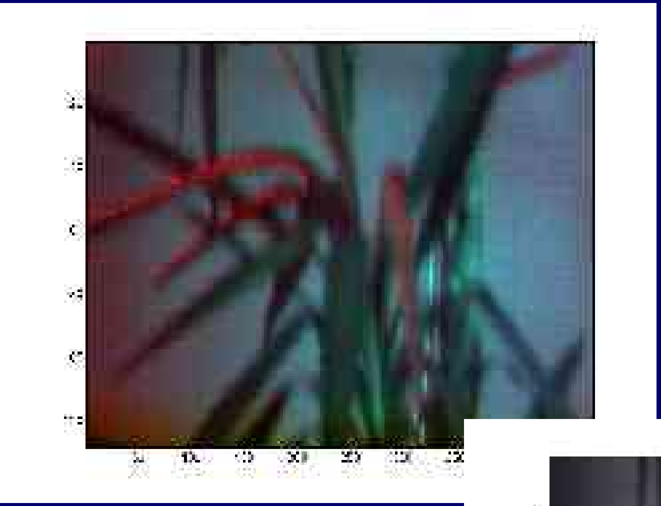
Closing the Loop: Examples

Detection of particular signatures via coded-aperture spectroscopy



Closing the Loop: Examples

Coded-aperture sensor: application



With optimized
spectral discrimination

Under broadband
illumination

Fake
vegetation

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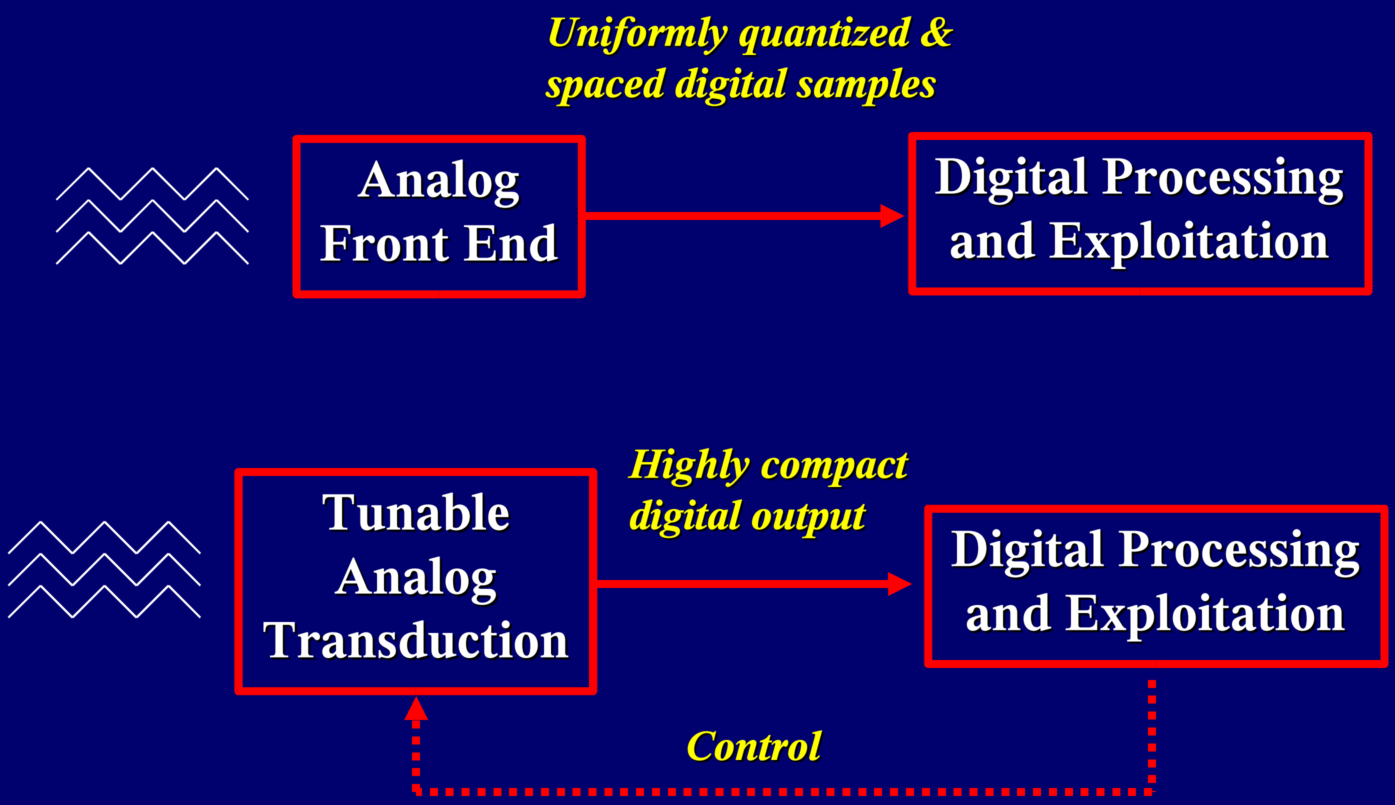
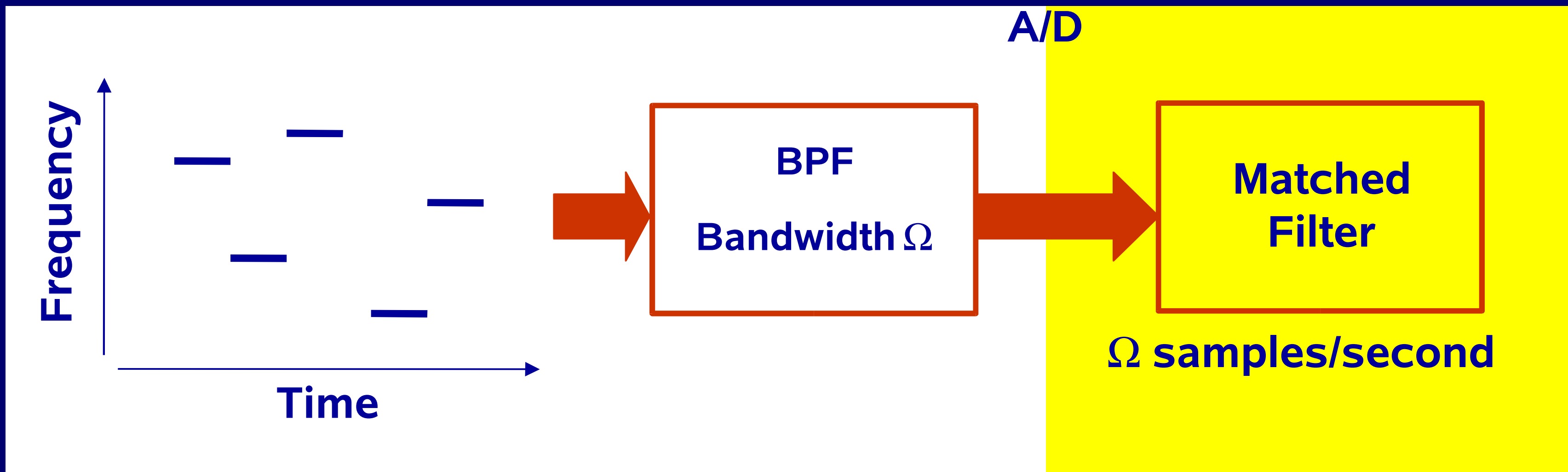
Physical-Layer Sensing & Processing

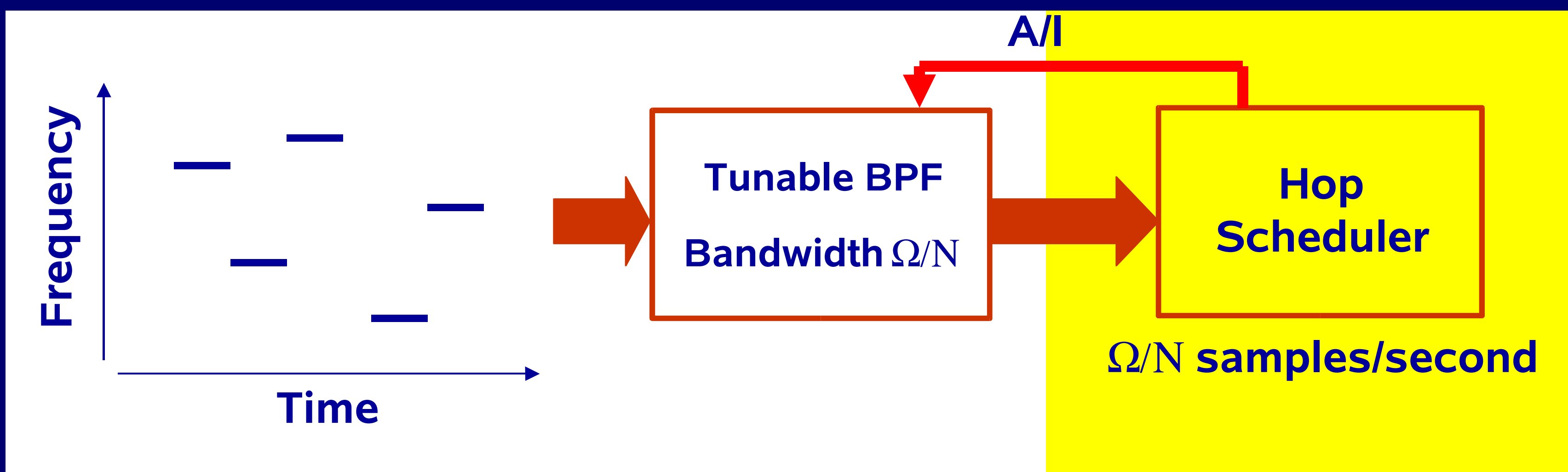
Analog-to-Information (A/I) Conversion



Physical-Layer Sensing & Processing

A/I Conversion: Frequency–Hopping Receiver



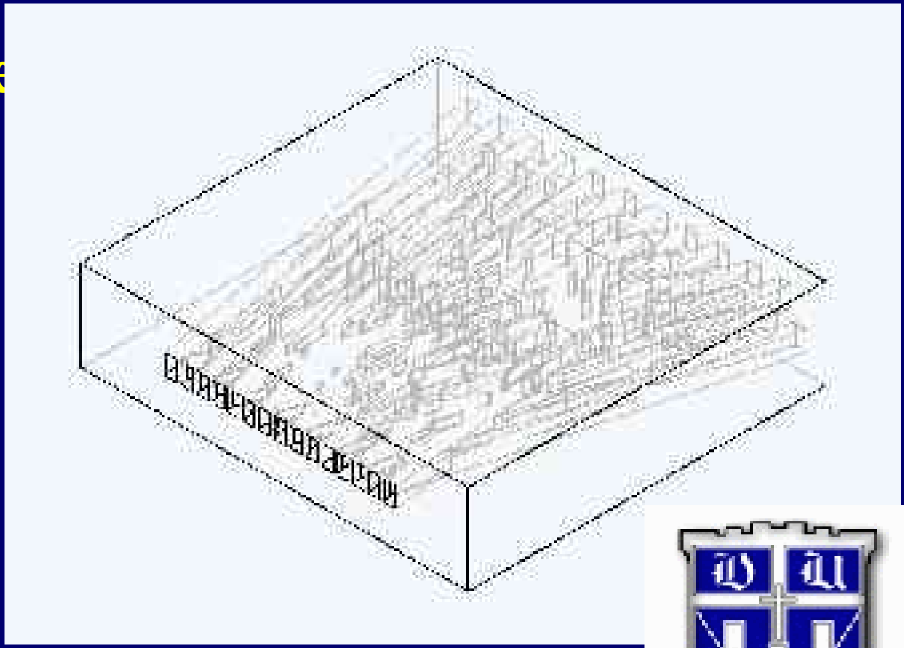


Physical-Layer Sensing & Processing

Optical Reference Structure Devices
Duke University

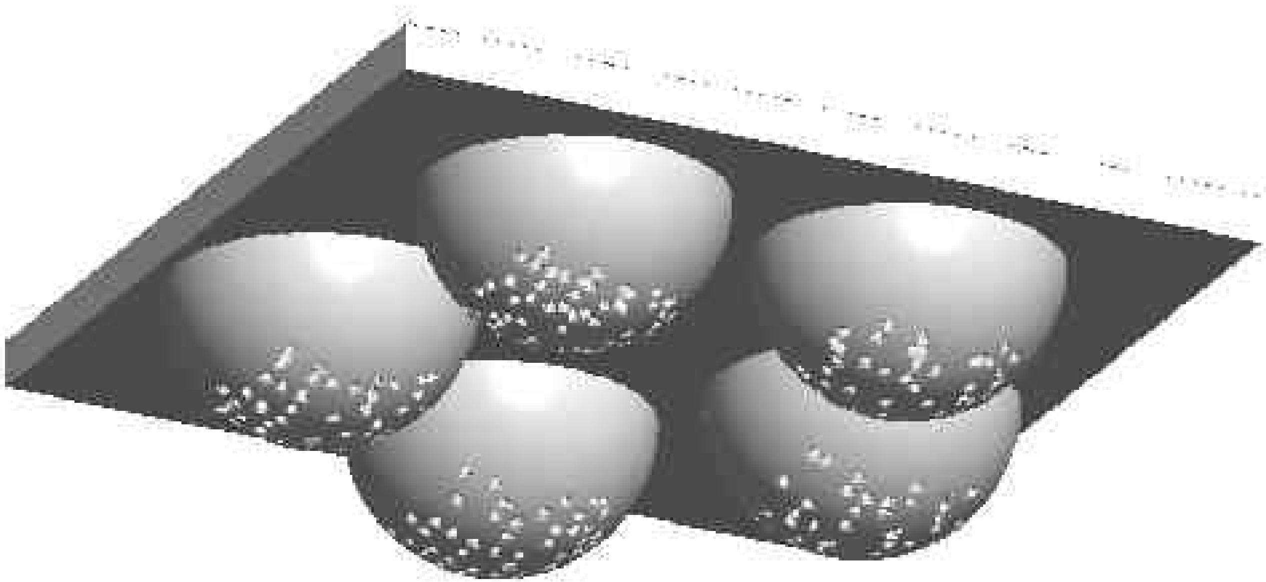
Introduction of known structure in optical path can…

- compute certain linear transforms optically before A/D
- regularize otherwise ill-posed inverse problems



Mapping desired transform description (optimally) to feasible structure design is an engineering challenge

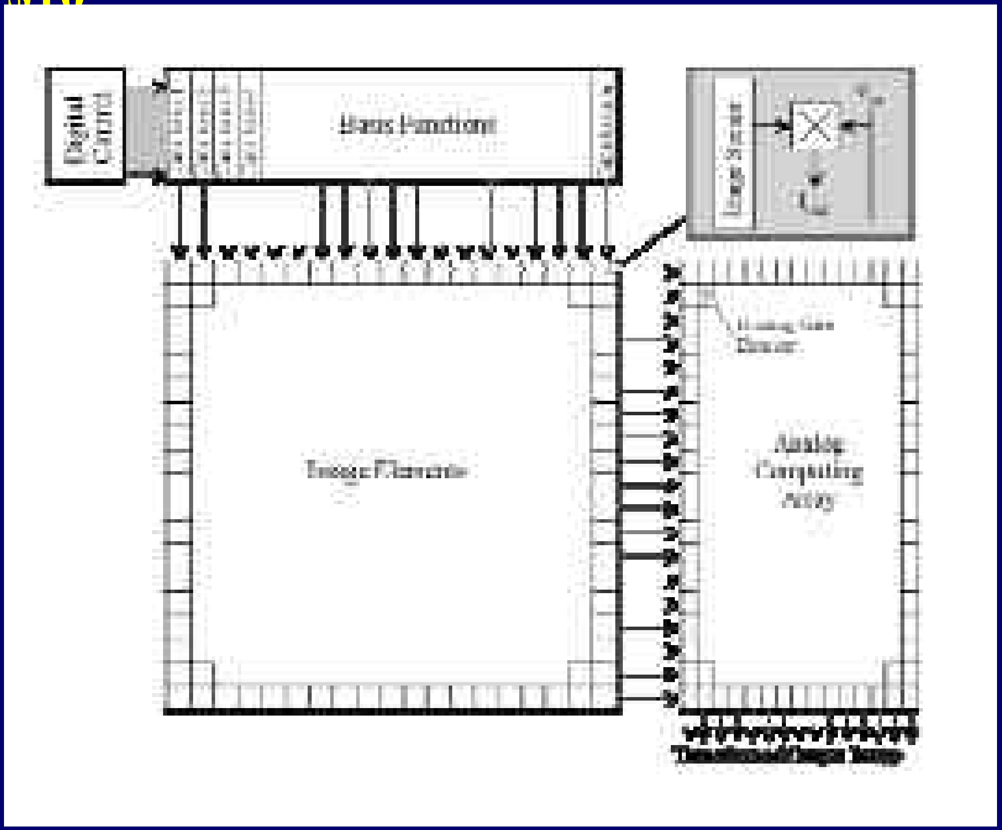
Physical-Layer Sensing & Processing

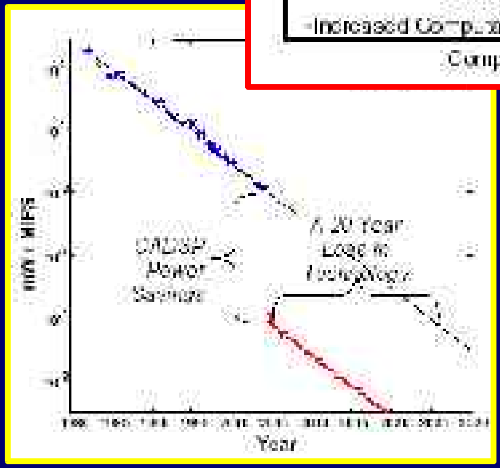


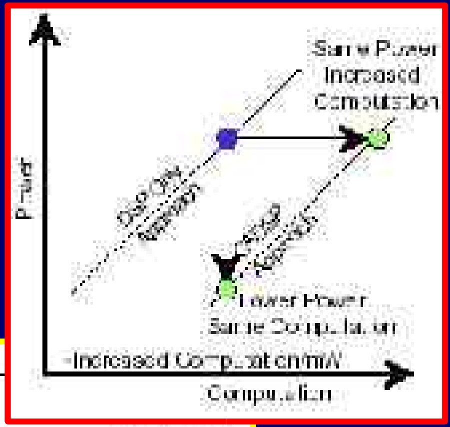
Physical-Layer Sensing & Processing

Combined Analog-Digital Signal Processing – CADSP (GA Tech)

- Advances in floating gate device technologies being applied to develop highly-flexible signal processing elements
- Potential five-year payoffs: 6 ICs → 1 IC; 2-3 W → 2-3 mW; $100 → $10

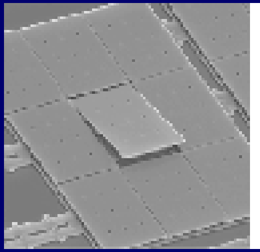






Waveforms for Active Sensing Program (WASP)

- Transmitter (& receiver) technologies have enjoyed great advances in the past two decades



  - Optical (micromirror arrays; SLMs; ultra-short (shaped) pulse and high-power lasers
  - RF (Agile, software-driven devices; tunable materials)

  - Acoustic (Air-coupled & liquid-coupled microsensors; agile software-controllable coherent array sources)

- Development of mathematical techniques to capitalize on these advances has not kept pace!

WASP Vision

Develop a unified, rigorous methodology for waveform design and scheduling in active sensing systems

Possible Objectives

- Adaptive spatio-temporal-spectral optical sensing
- Libraries of signal classes for diversity sensing
- Real-time, closed-loop adaptive waveform design
- Coordinated irregular pulsing
- Bio-inspired pulse scheduling

Status

- Program proposal under development
- Anticipated start in FY 2005

Another upcoming MTO/DSO program: A/I Conversion

End

"The wealth of your practical experience
with sane and interesting problems
will give to mathematics
a new direction and a new impetus."

— Leopold Kronecker to Hermann von Helmholtz