Microsystems Technology Office

Proposers Day

September 20, 2016

Distribution A: Approved for public release

Microsystems Technology Office

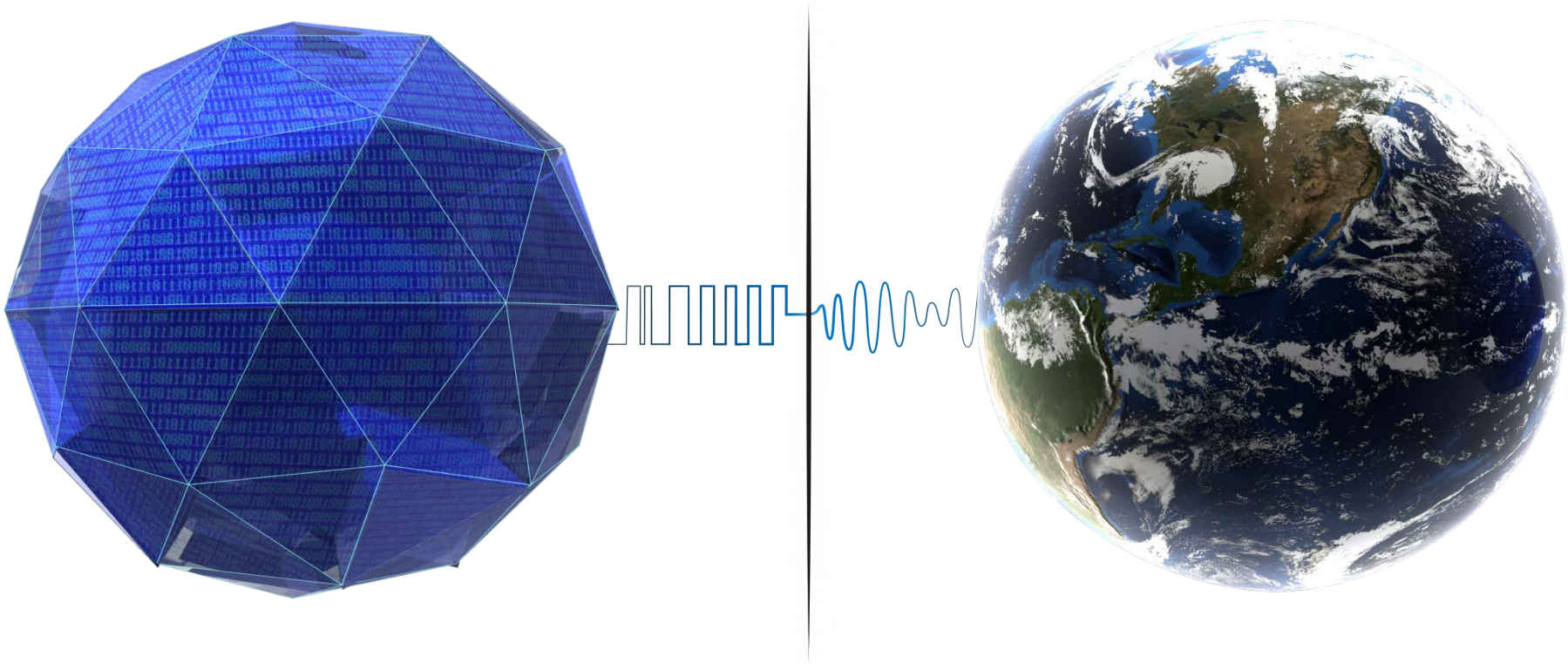
Bill Chappell, Director MTO
Yifty Eisenberg, Deputy Director MTO

Proposers Day

September 20, 2016

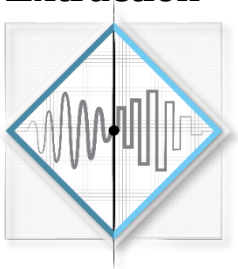
Distribution A: Approved for public release

MTO c.2016: The bridge between the digital and physical domains



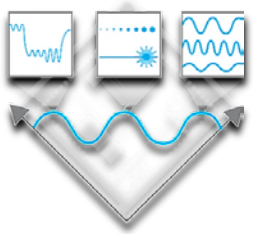
MTO c.2016

Tactical Information Extraction



Globalization

Spectrum & Physics Interfaces

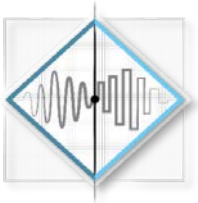


Processing *Learning* *Application* *Speed* *Leveraging* *Security* *RF* *Optics* *Sensors*

Distribution A: Approved for public release

MTO strategy

Tactical Information Extraction



Processing
- UPSIDE
- PERFECT

Learning
- Cortical Processor
- HIVE

Application
- ARC
- SC2

Develop processing architectures for next-generation machine learning

Globalization

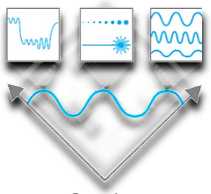
Speed
- CRAFT
- CHIPS

Leveraging
- DAHI
- ICECool
- SPADE
- STARnet

Security
- VAPR
- SHIELD
- MAGIC EYE
- IRIS

Move from fear to exploiting the new technology approach

Spectrum & Physics Interfaces



RF
- ART
- ACT
- MPC
- Disarmer
- TROPHY
- HERMES
- SPAR
- M3IC
- HAVOC

Optics
- Endurance
- FLASH
- LUSTER
- DODOS
- MOABB
- WIRED
- LOTS

Sensors
- N-ZERO
- microPNT
- PRIGM
- ACES

Expand our lead in the physical realm

Distribution A: Approved for public release

MTO Proposers Day

Spectrum and Physics Interfaces

Expand our lead in the physical realm

Distribution A: Approved for public release

Integration: Defining how we'll fight tomorrow

1990 | 2000 | 2010 | Today | 2020 | 2030

Power

MIMIC Program

GaAs

WBGS-RF Program

GaN

GaN +

ICECool — Better Cooling

MPC — Unconstrained Waveforms

NeXT — Higher Frequencies

Integration

Digital and low frequency silicon

TEAM
SiGe and RF CMOS

SMART/ELASTx
High freq. arrays

RF Silicon

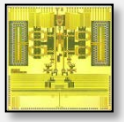
Early transistor Research (1940s)

First commercial BiCMOS foundry offering (5HP)

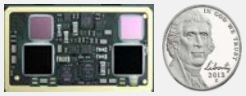
ACT Program

Massive integration and digital to the antenna

Complex circuit board

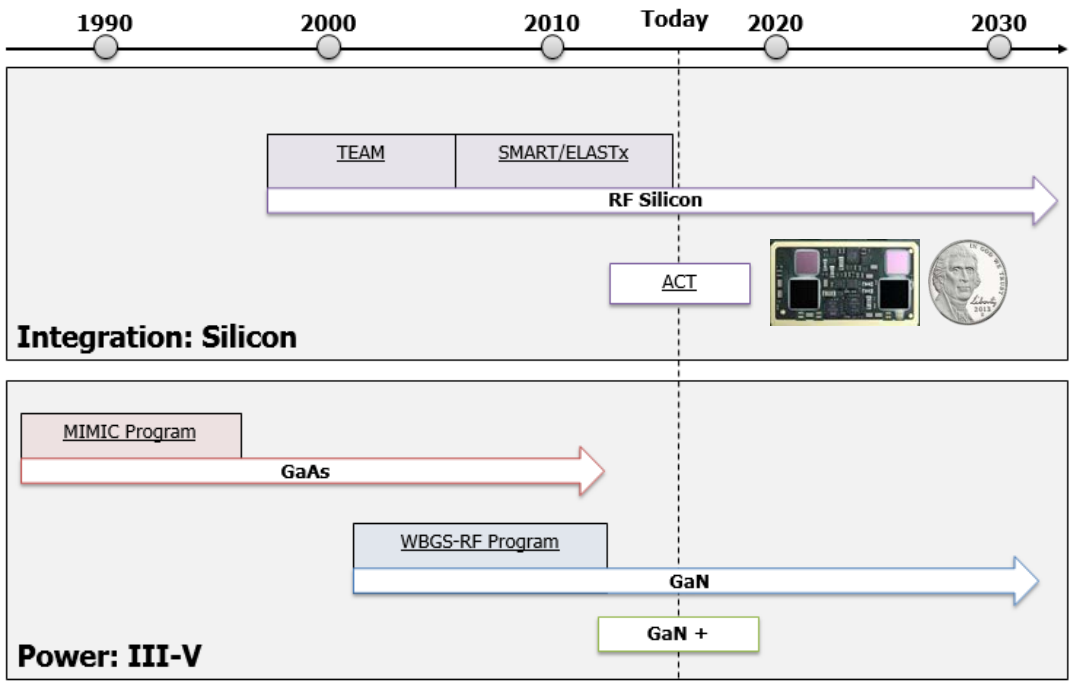


SoC

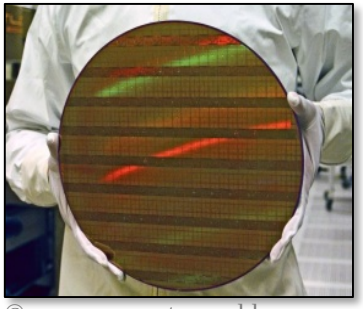


Distribution A: Approved for public release

The best of power and integration



Commercial Si CMOS fab



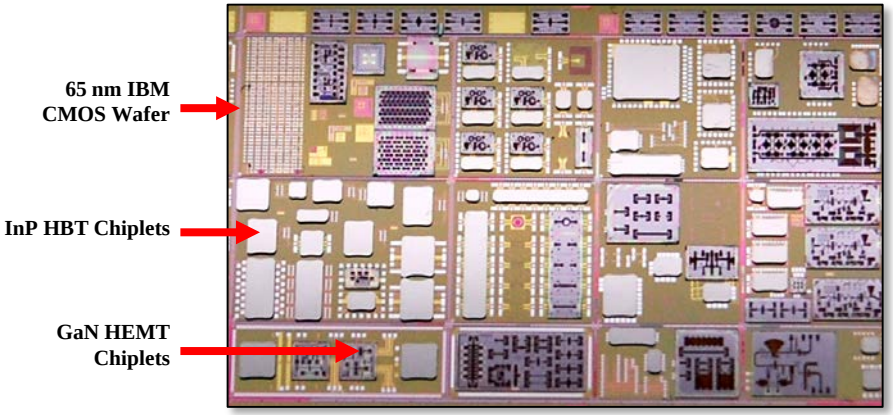
© www.computerworld.com

DoD Exotic material fab

© www.martini-tech.com

DoD Exotic material fab

© www.ise.fraunhofer.de



Distribution A: Approved for public release

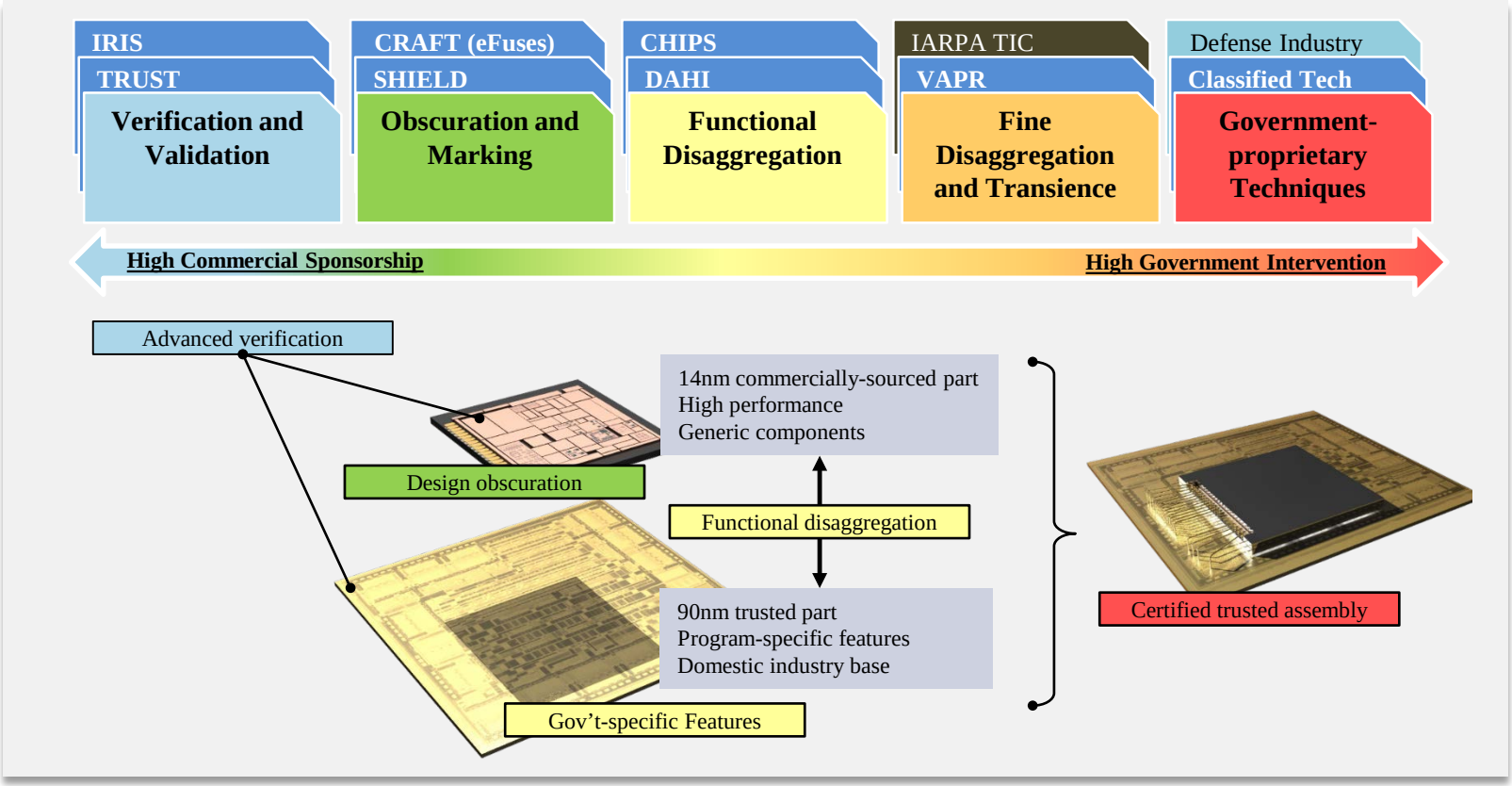
MTO Proposers Day

Globalization

Move from fear to exploiting the new technology approach

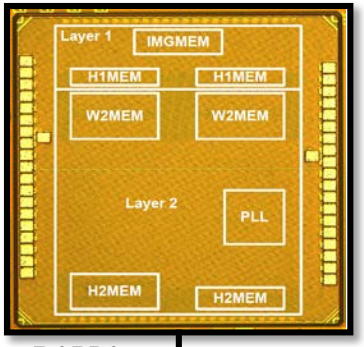
Distribution A: Approved for public release

Trust through technology



Going from innovation to application

Innovation



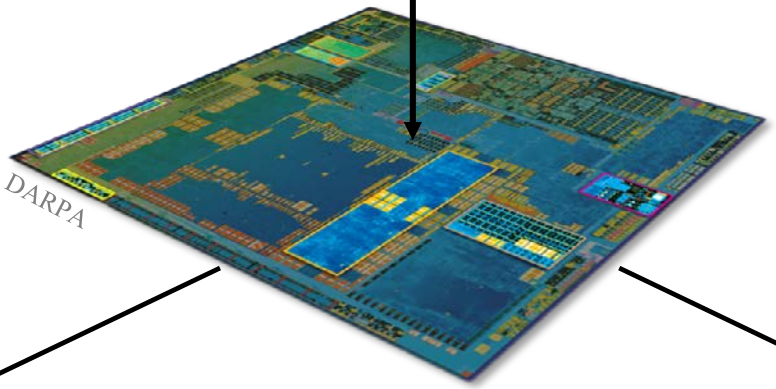
DARPA

Grad Student Idea

Throughput: 900 GOPS (effective)

Power efficiency: 6.37 TOPS/W

Most power efficient CNN chip



DARPA

Commercial

© GraphicRiver/Envato

Military

© Raytheon

Distribution A: Approved for public release

MTO Proposers Day

Tactical Information Extraction

Develop processing architectures for next-generation machine learning

Distribution A: Approved for public release

First-wave AI technologies

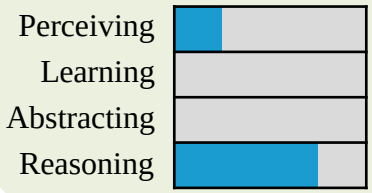
DESCRIBE

Handcrafted Knowledge

Engineers create sets of rules to represent knowledge in well-defined domains

Enables reasoning over narrowly defined problems

No learning capability and poor handling of uncertainty



Planning tools

Source: mjc2.com

Command Post of the Future

Source: www.cerdec.army.mil

Software analysis

Source: Oregon State University

Expert systems

Source: Intuit

Distribution A: Approved for public release

Second-wave AI technologies

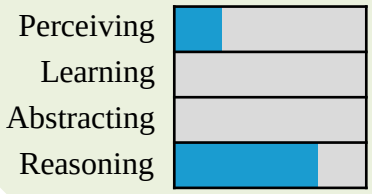
DESCRIBE

Handcrafted Knowledge

Engineers create sets of rules to represent knowledge in well-defined domains

Enables reasoning over narrowly defined problems

No learning capability and poor handling of uncertainty



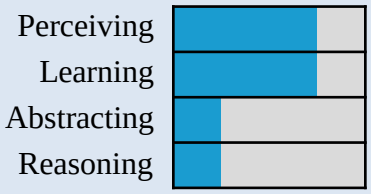
PREDICT

Statistical Learning

Engineers create statistical models for specific problem domains and train them on big data

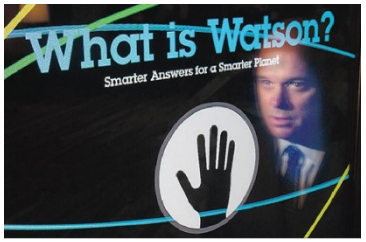
Nuanced classification and prediction capabilities

No contextual capability and minimal reasoning ability



Source: thrillist.com

Source: wikimedia.org



Source: windsorstar.com

AlphaGo

Source: gobelluno.it

Distribution A: Approved for public release

A powerful example of second-wave AI

Common Items Computers Discovered

From 10 million YouTube random image captures

Faces

Human bodies

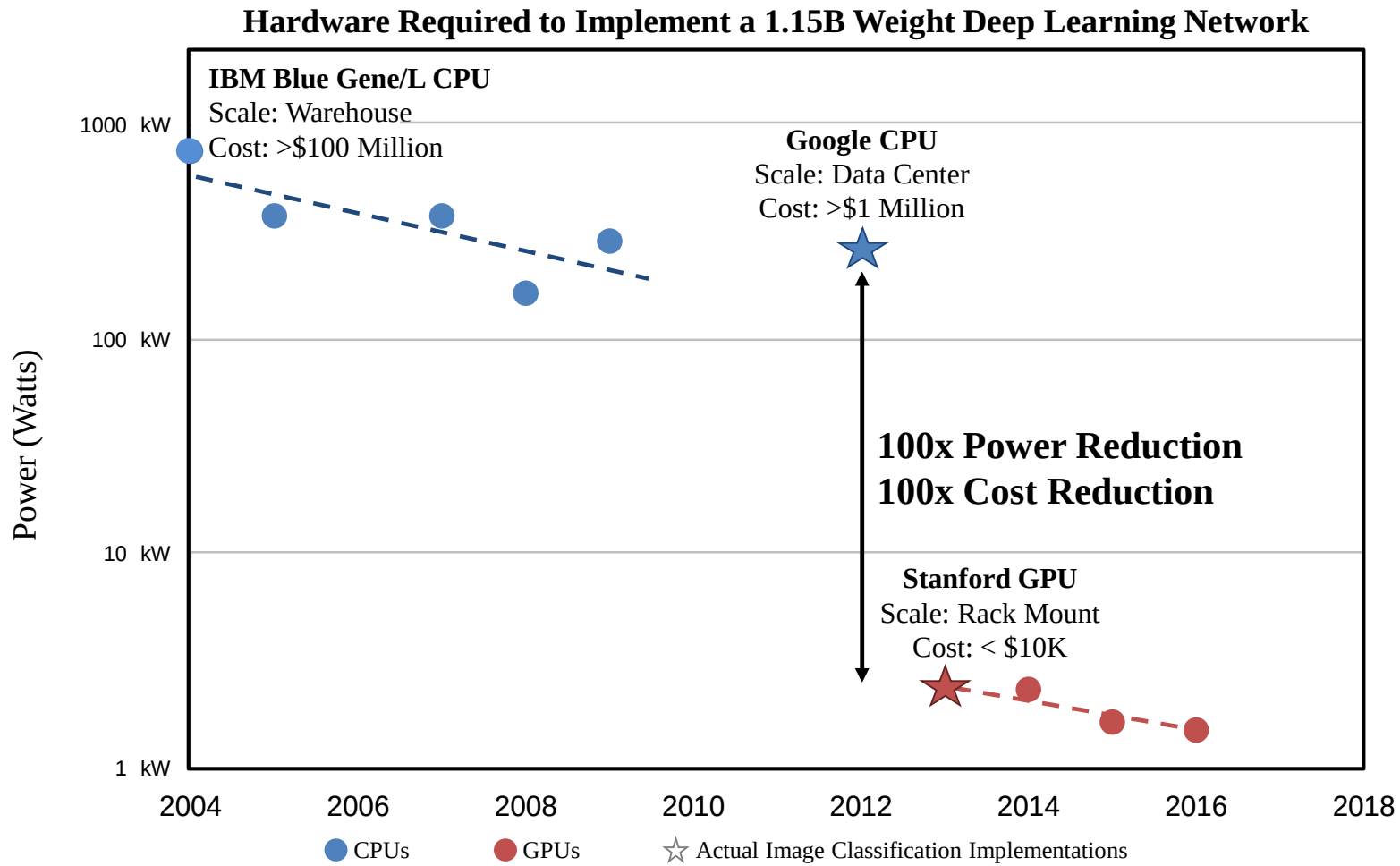
Cats

Unsupervised learning enables computers to discover patterns in unlabeled data sets

*(Kwok Le, Andrew Ng, Building high-level features using large-scale unsupervised learning. ICML 2012)

Distribution A: Approved for public release

Hardware has played a vital role in advancing AI



The GPU made Deep Learning functional and accessible by dramatically reducing the cost and processing power relative to CPU's.

Distribution A: Approved for public release

Future third-wave AI technologies

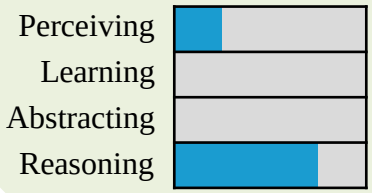
DESCRIBE

Handcrafted Knowledge

Engineers create sets of rules to represent knowledge in well-defined domains

Enables reasoning over narrowly defined problems

No learning capability and poor handling of uncertainty



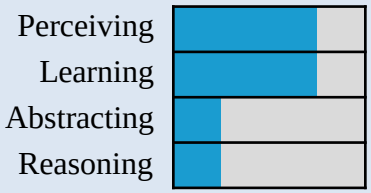
PREDICT

Statistical learning

Engineers create statistical models for specific problem domains and train them on big data

Nuanced classification and prediction capabilities

No contextual capability and minimal reasoning ability



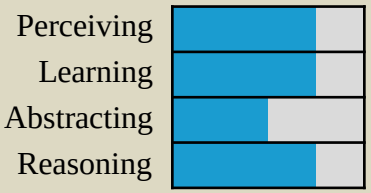
EXPLAIN

Contextual adaptation

Engineers create systems that construct explanatory models for classes of real world phenomena

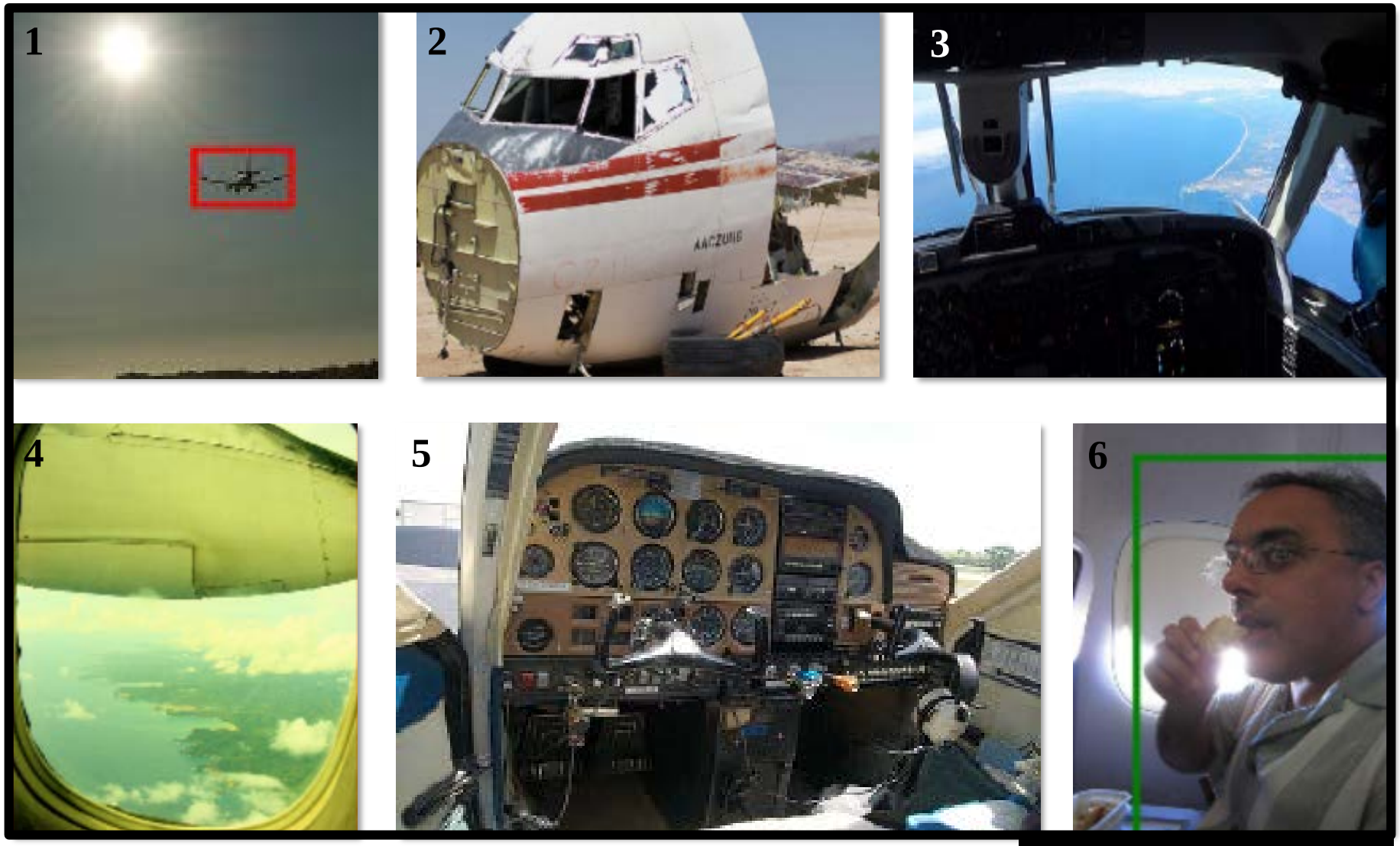
Natural communication among machines and people

Systems learn and reason as they encounter new tasks and situations



Distribution A: Approved for public release

The importance of context



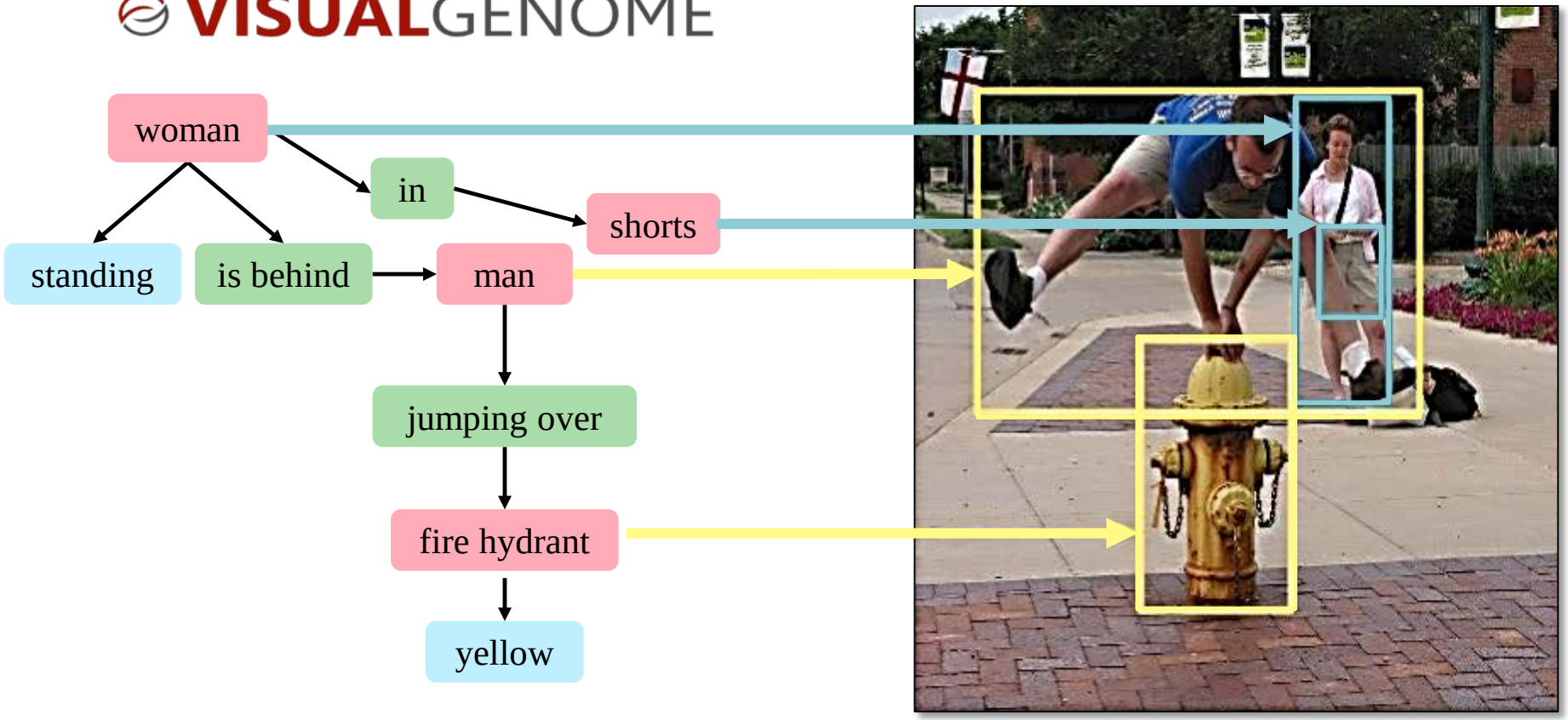
Source: Todd Hylton; Brain Corps
Funded on Cortical Processor Seedling

Distribution A: Approved for public release

Contextual adaptation requires an understanding of relationships

Stanford University

VISUALGENOME



Source: Stanford; Fei-Fei Li

objects | attributed | relationships

Source: Stanford; Fei-Fei Li
Funded by DARPA Cortical Processor

Distribution A: Approved for public release

www.darpa.mil

Distribution A: Approved for public release

Precision Measurement and Sensing

Robert Lutwak
Program Manager
Microsystems Technology Office

Proposers Day

September 20, 2016

Distribution A: Approved for public release

About Me

- 30 years experience measuring things
  - PhD Atomic and Optical Physics (MIT, 1997)
  - Post-Doc at NIST
  - 15 years as industrial scientist developing atomic clocks

Microsemi CSAC
≈100 mW, ≈ 15 cm^3, ≈ $1000

- DARPA Performer turned Program Manager
  - Principal Investigator on DARPA/MTO Chip-Scale Atomic Clock (CSAC) program
  - Symmetricom CSAC released to production in 2011
  - Joined DARPA/MTO in 2013

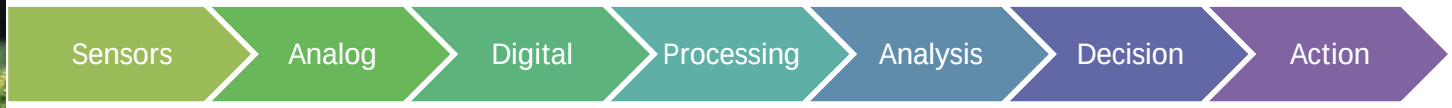
- Primary Interest: Precision sensors for enhanced situational awareness
  - Move modern measurement physics from the laboratory to the field
  - Leverage modern atomic physics and quantum optics, microelectromechanical systems (MEMS), integrated photonics, novel materials and architectures

DISTRIBUTION STATEMENT A. Approved for public release; distribution is unlimited.

Situational Awareness and Appropriate Action

Real World

Source: Wikicommons



Garbage in/Garbage out: MTO has programs addressing every chevron of the decision chain. Every step does its part to improve upon imperfect sensor performance. Improved sensor performance is the foundation for improved decision making and appropriate action.

Explosive growth: Industry analysts now predict that there will be **one trillion** sensors deployed worldwide by 2022. *(source tsensors.com)*

Sense what? Position, orientation, motion, and time; temperature, magnetic field, and weather; sound, images, and electromagnetic radiation; etc.

What matters?

Precision (how many digits) is necessary but not sufficient. ***Accuracy*** (how many *useful* digits) ultimately limits field performance.

Successful transition to wide deployment requires low cost, size, weight, and power (CSWaP)

DISTRIBUTION STATEMENT A. Approved for public release; distribution is unlimited.

Current and Ongoing Programs

- Chip-Scale Combinatorial Atomic Navigator (C-SCAN)
  - Advanced gyroscopes and accelerometers based on modern atomic physics
- Direct On-chip Digital Optical Synthesis (DODOS)
  - Control optical frequency (and wavelength) with the accuracy of electronics
- Advanced Inertial Micro Systems (AIMS)
  - Exploring future inertial sensors based on novel architectures of photonics, MEMS, and photonic MEMS
- Atomic Clock with Enhanced Stability (ACES)
  - Apply modern physics techniques to develop a battery-powered atomic clock with 1000X improved performance over prior CSAC.
- High Dynamic Range Atomic Magnetic Gradiometer (HDRAMG)
  - 1000X improved magnetic sensing outside of shielded environments

DISTRIBUTION STATEMENT A. Approved for public release; distribution is unlimited.

Example: Future Fabulous Accelerometer

Mechanical Things
- 100 ppm is hard
- 1 ppm is heroic

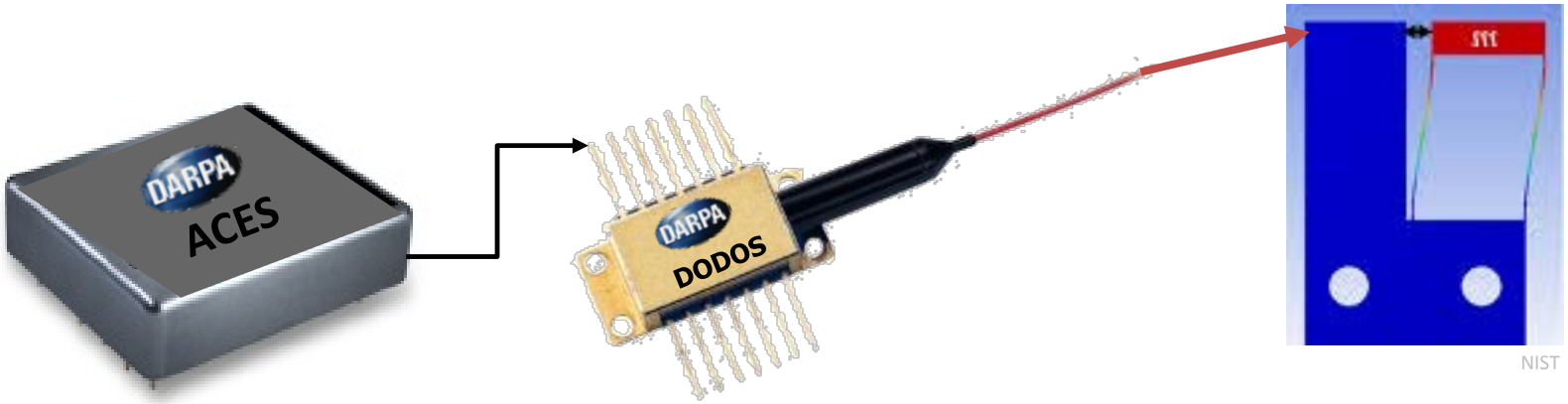
©wikicommons.com

vs.

©wikicommons.com

Clocks
- 1 ppm is child's play
- 1 ppb is hard
- 1 **pp 10^{15}** is heroic

How do we leverage clock performance into mechanical measurement?



NIST

Clock with guaranteed accuracy of one part in 10^{13} under all conditions

Convert clock to optical wavelength with one part in 10^{15} accuracy

Measurement of MEMS proof mass displacement in units of optical wavelength

DISTRIBUTION STATEMENT A. Approved for public release; distribution is unlimited.

Seedling Interests

- Novel sensor modalities and architectures
  - Atomic clocks
  - Magnetometers
  - Inertial sensors (gyroscopes and accelerometers)
  - Gravimeters

- Component technologies for integrated atomic sensors:
  - Application-specific laser sources
  - Integrated photonics and atomtronics for clocks, magnetometers, and inertial sensors
  - Magnet-free ultra-high vacuum pumps
  - Free-space optical shutters

All at Micro-CSWaP

- **What makes a good seedling?**
  - Novel, high risk idea worth trying quickly
  - Focused effort addresses the proof (or disproof) of concept without much baggage
  - Well-defined goals and metrics so we know where we're at when we get there
  - "Yes" and "No" are both good results, "we didn't get it working" is not.

DISTRIBUTION STATEMENT A. Approved for public release; distribution is unlimited.

Robert.Lutwak@darpa.mil

DISTRIBUTION STATEMENT A. Approved for public release; distribution is unlimited.

Creating Revolutionary Imaging Technologies

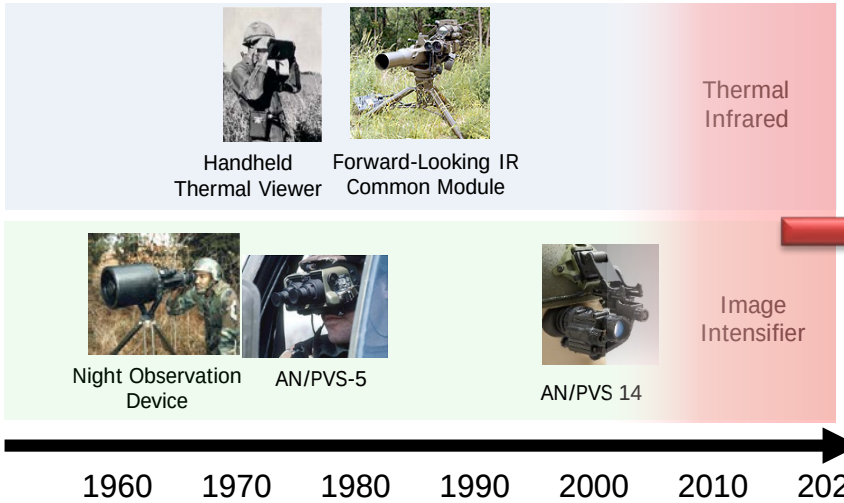
Dr. Jay Lewis
Program Manager
Microsystems Technology Office

Proposers Day

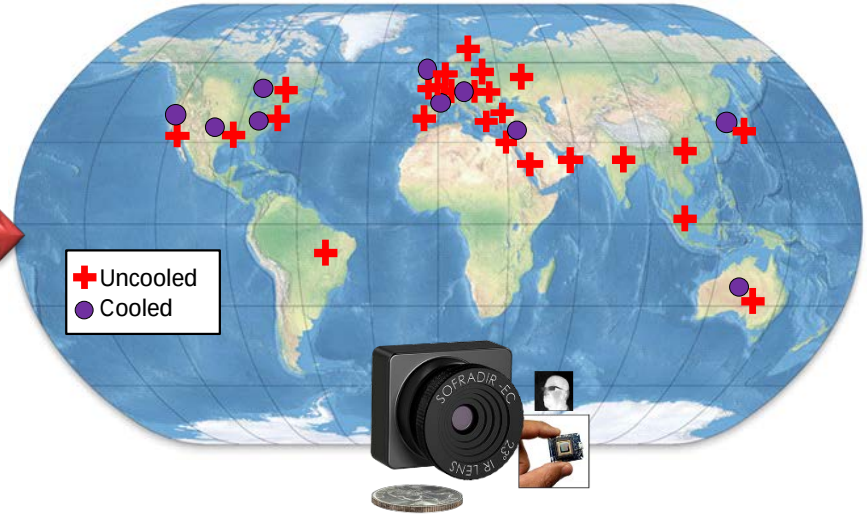
September 20, 2016

Distribution A: Approved for public release

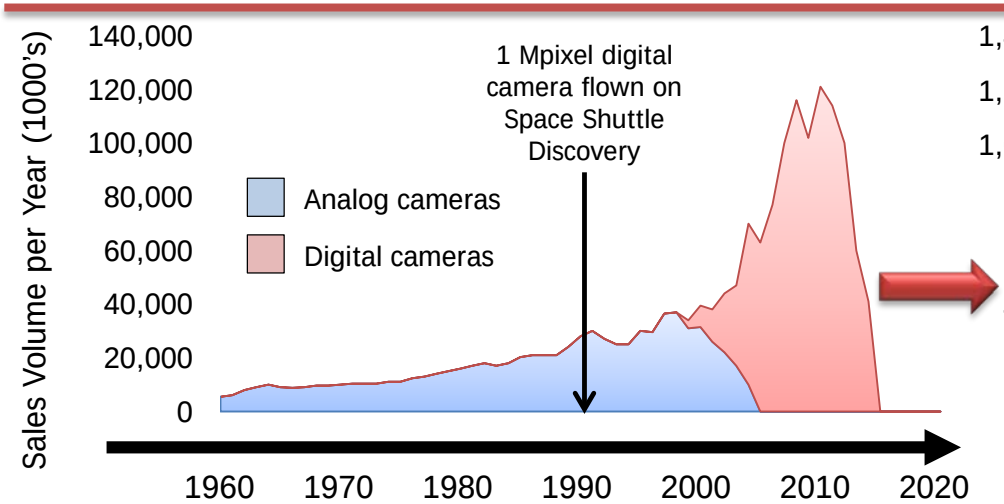
A Brief History of Imaging and the DoD



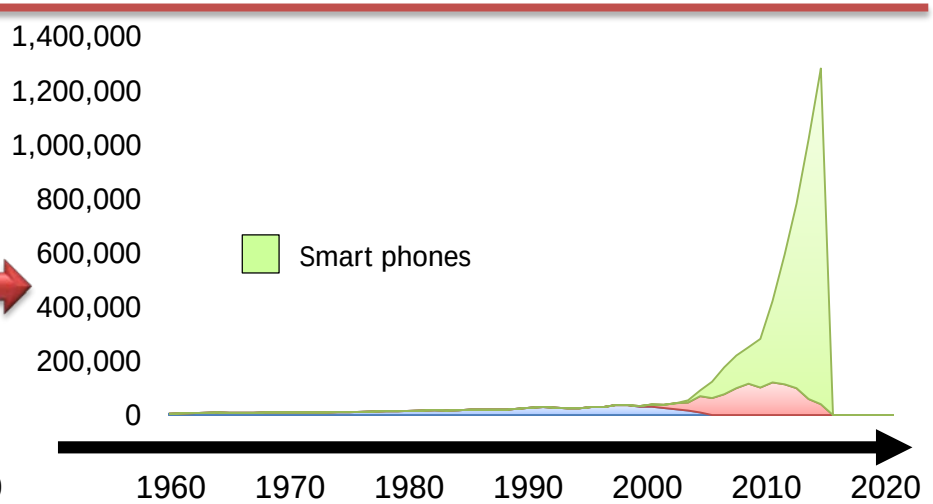
The U.S. owns the night



Night vision technology is widely proliferated



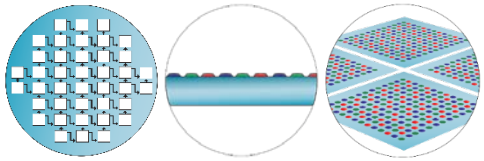
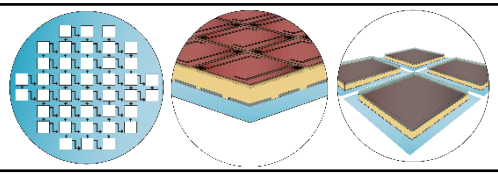
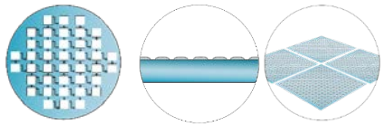
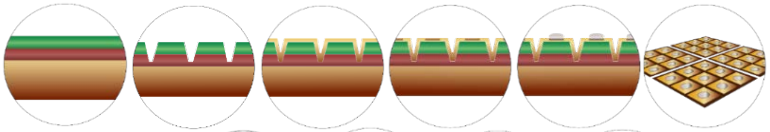
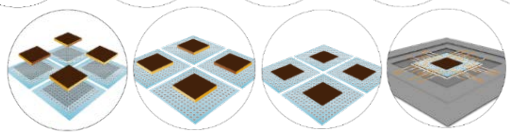
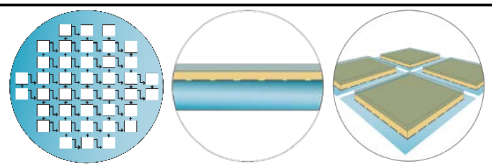
Government investment is a driver for imaging technology



Complexity is driven by high volume commercial designs

(Source: petapixel.com, adapted from Gartner, Inc. and Camera & Imaging Products Association data

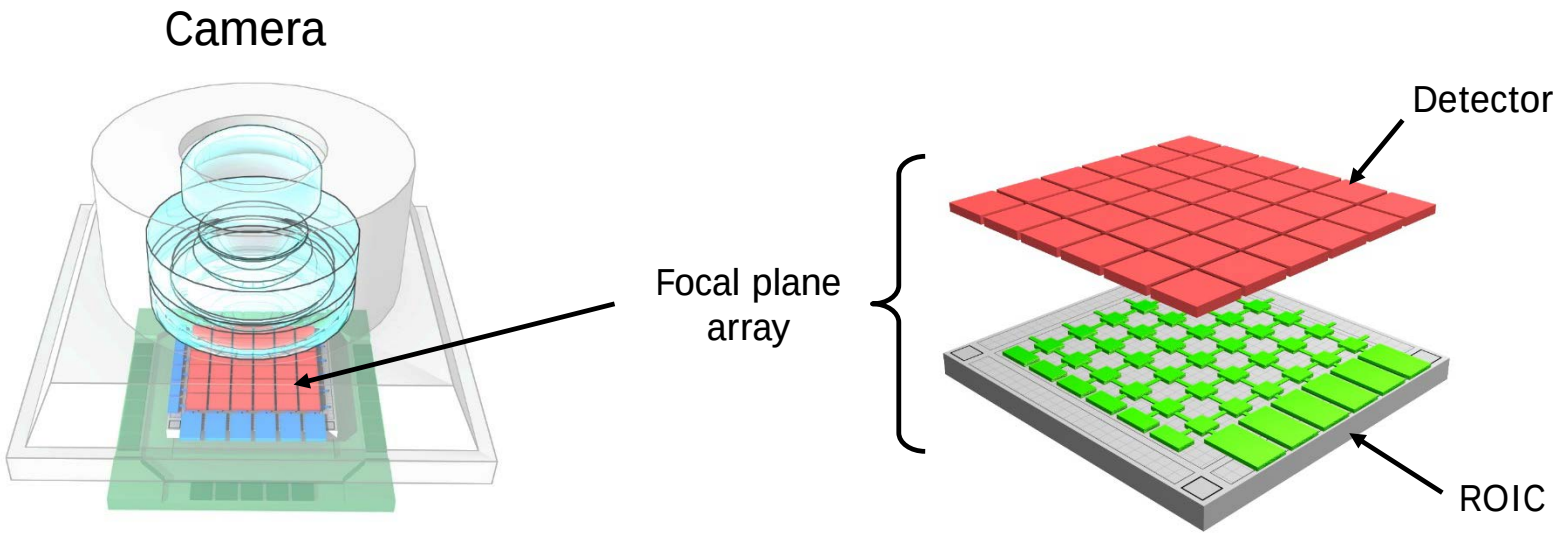
Wafer-Scale Infrared Detectors (WIRED)

Technology	Scale	Processes	Cost
Visible CMOS	Wafer Scale		**$15**
LWIR Microbolometer	Wafer Scale		**~$1k**
SWIR IRFPA* MWIR IRFPA	Die Scale	ROIC →  Detector →  Die Scale Processing → 	**~$15-30k**
WIRED SWIR, MWIR IRFPA	Wafer Scale		**< $1k**

*IRFPA = Infrared focal plane array

Disordered materials enable large-area processing, and performance advantages in operating temperature and resolution

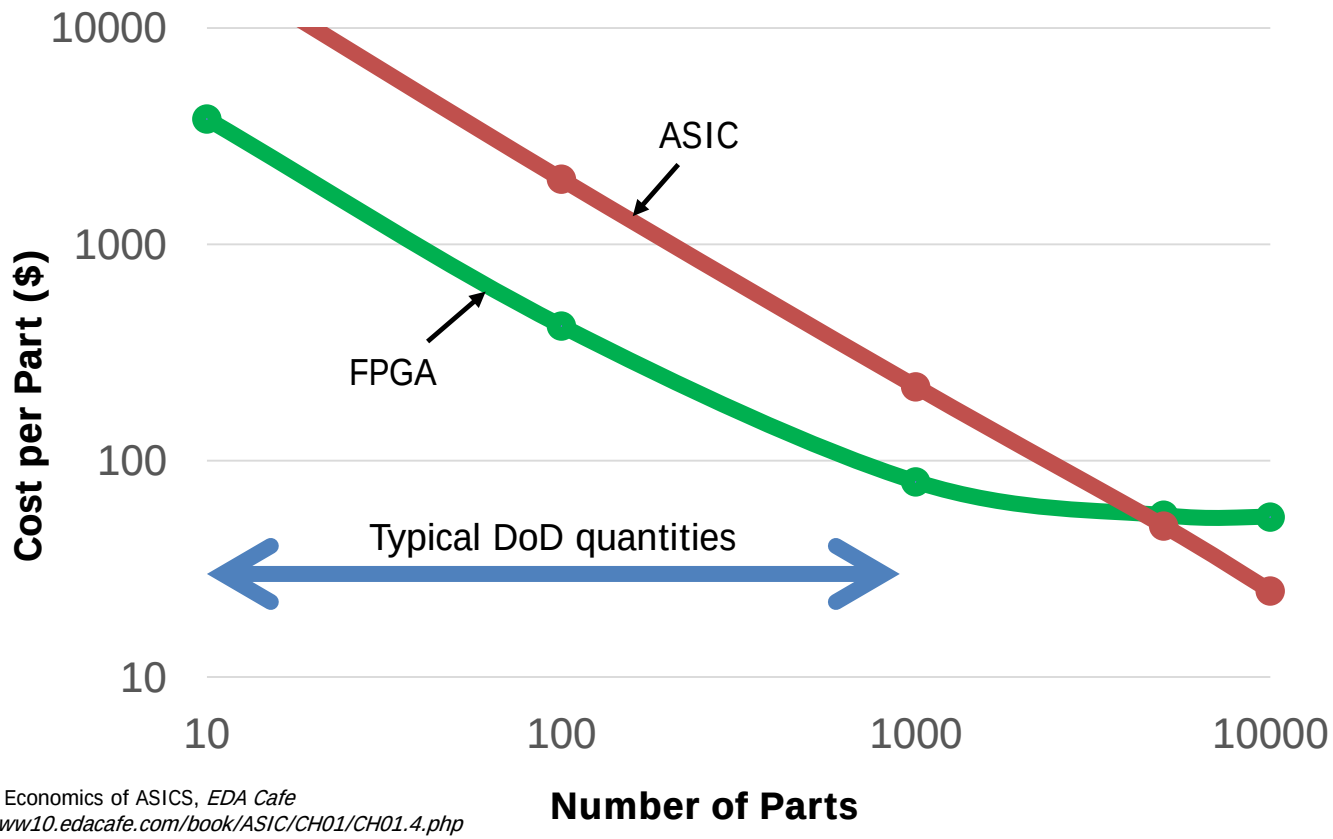
Reconfigurable Imaging (ReImagine)



Primary ROIC Functions	ROICs Today	ReImagine
1. Sample data from the detector (per pixel)	Optimized for type of detector, application, conditions	**Adapt** for any detector, sample at any spatial or temporal resolution, framing or asynchronous readout, or active time of flight
2. Transfer data from the array to the periphery	Global process, inflexible	**Random access** to data, versatile region of interest operation
3. Transfer data off the chip	Imposes resolution vs. framerate limit	Enables **complex measurements** with high resolution context imagery

The objective of ReImagine is to develop a **software-reconfigurable** ROIC architecture to enable **multi-mission functionality** in a single camera

Programmability Enables Complexity at Low Volume



Source: Economics of ASICS, *EDA Cafe*
http://www10.edacafe.com/book/ASIC/CH01/CH01.4.php

FPGA model offers:

- Fastest route from concept to demonstration
- Cutting edge capabilities in low volume production

ReImagine Technical Areas

- **Technical Area 1:** Single or multi-color passive imager architecture and algorithms
- **Technical Area 2:** Hybrid active/passive imager architecture and algorithms
- **Technical Area 3:** Innovative concepts for imaging systems with internal feedback

BAA: https://www.fbo.gov/spg/ODA/DARPA/CMO/DARPA-BAA-16-56/listing.html

Proposers Day SN: https://www.fbo.gov/spg/ODA/DARPA/CMO/DARPA-SN-16-68/listing.html

September 30, 2016, Arlington, VA

www.darpa.mil

Software Defined Programs

Dr. Tom Rondeau
Program Manager
Microsystems Technology Office

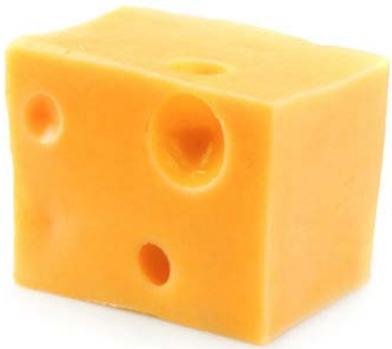
Proposers Day

September 20, 2016

Distribution A: Approved for public release

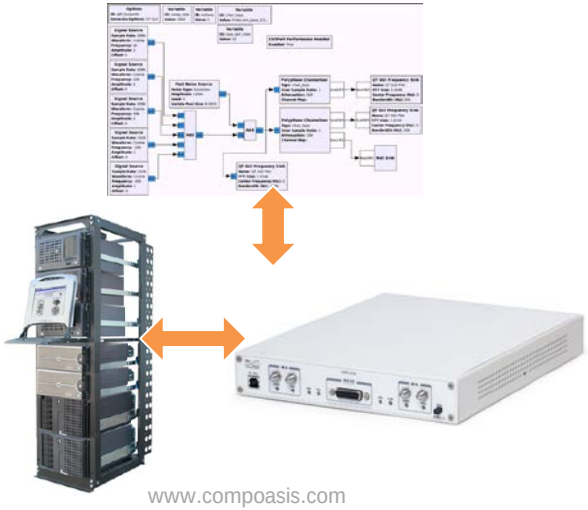
GNU Radio

The Free & Open Software Radio Ecosystem



www.fastmoving.co.za/events/marketing-178/sa-cheese-festival-give-small-cheese

Today's SDRs

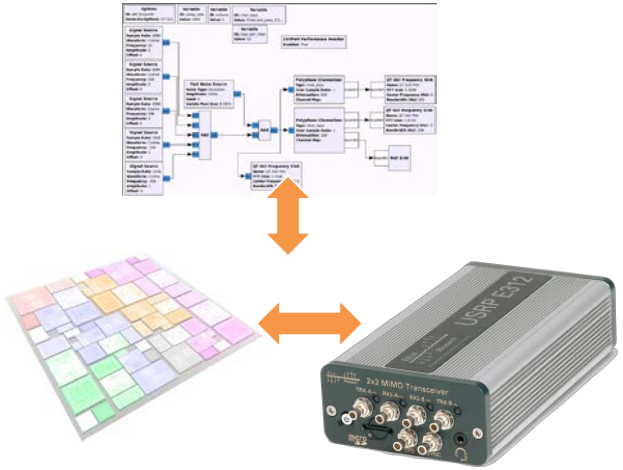


www.compoasis.com

Deployed SDRs

www.google.com/images

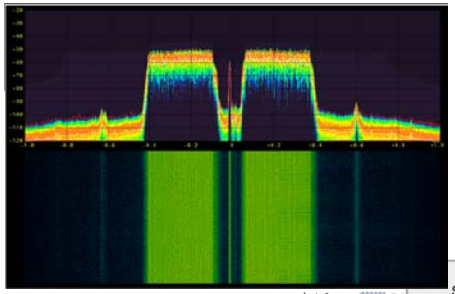
Tomorrow's SDRs

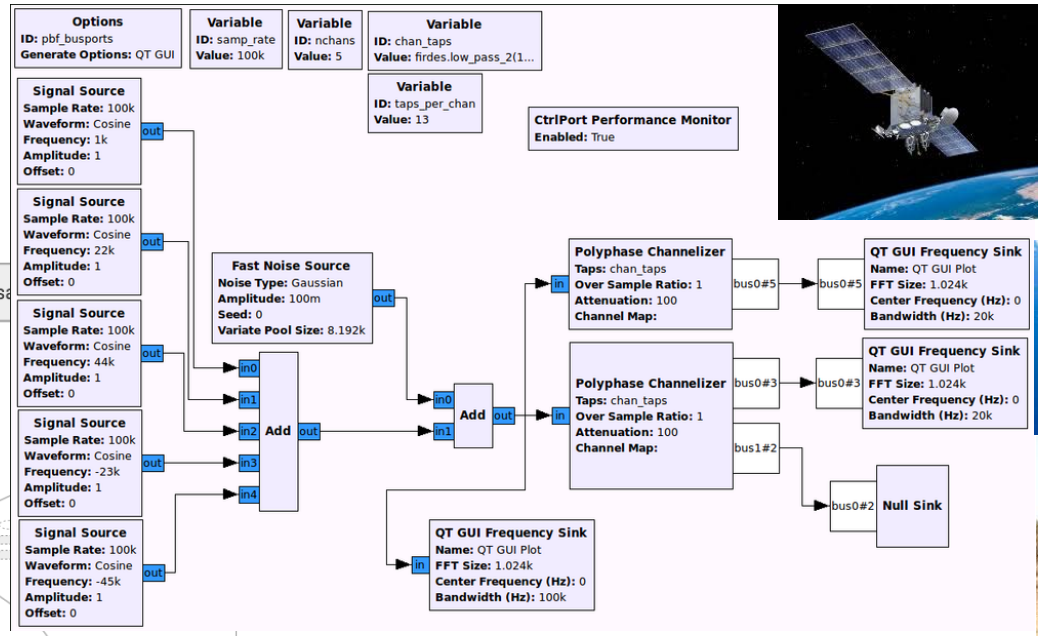


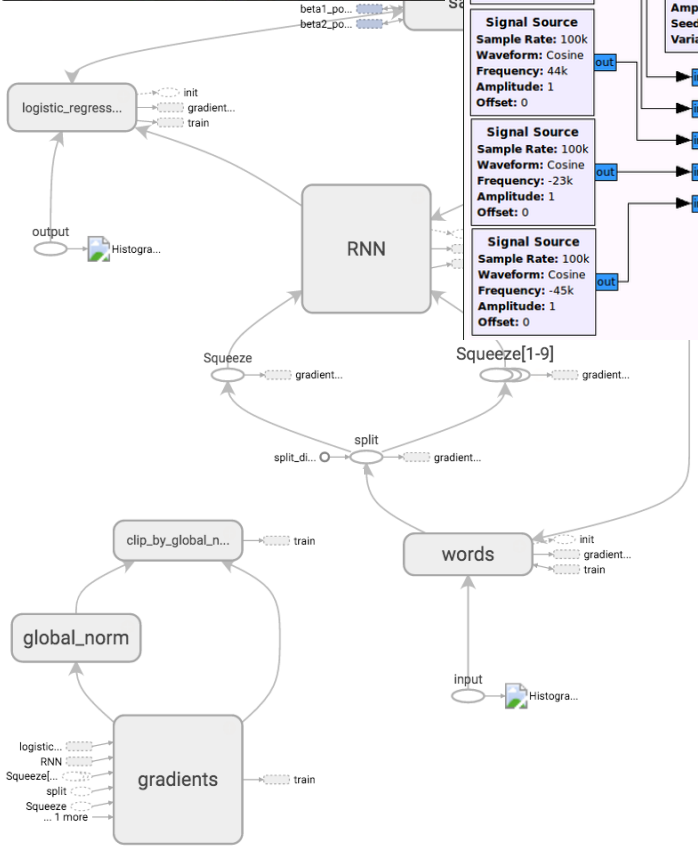
www.ettus.com

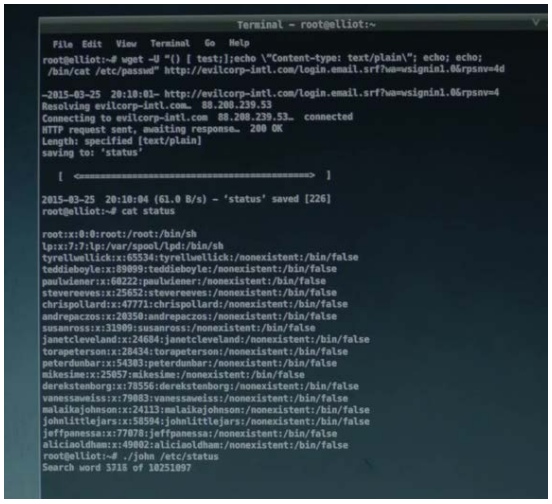
Distribution Statement "A" (Approved for Public Release, Distribution Unlimited)

All of our physical systems rely on software

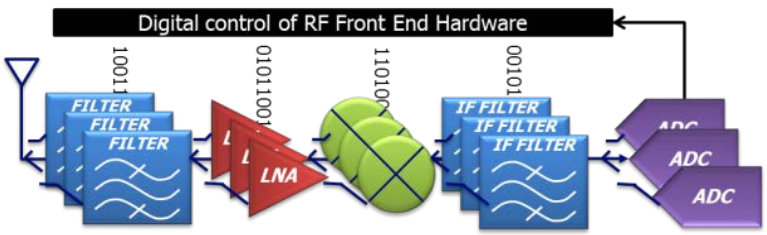




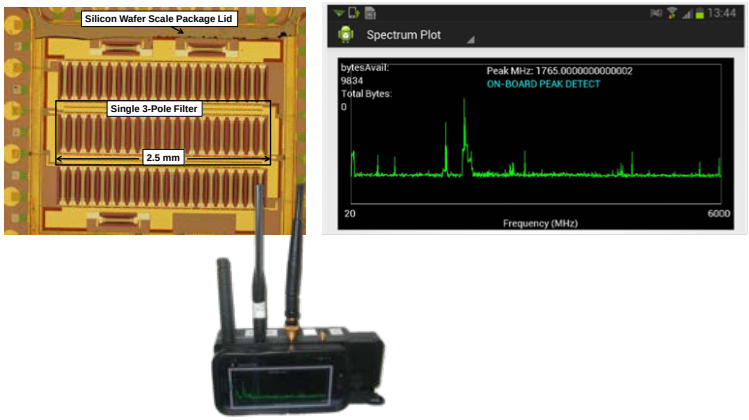




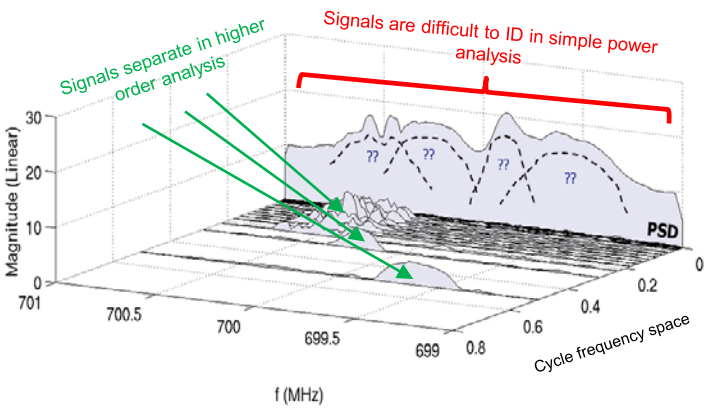
RF-FPGA: Highly Flexible Transceiver



Chip-Scale Spectrum Analyzer(CSSA): Instantaneous spectrum view



Cognitive radio Low-energy signal Analysis Sensor Ics (CLASIC): Signal Identification



Distribution Statement "A" (Approved for Public Release, Distribution Unlimited)

The Domain Space of Software Radio

Domain

Comms

EW

Radar

Applications

LTE

5G

Link 16

mmWave

HF

DRFM

SIGINT

Jamming

EA

PNT spoofing

EP

SAR

Targeting

GMTI

IFF

Tracking

Detection

Imaging

Virtualized Processing

BIST and monitoring

Back ends

I/O

Memory

Accelerators

CPUs

Networks (assign end points, speed, QoS)

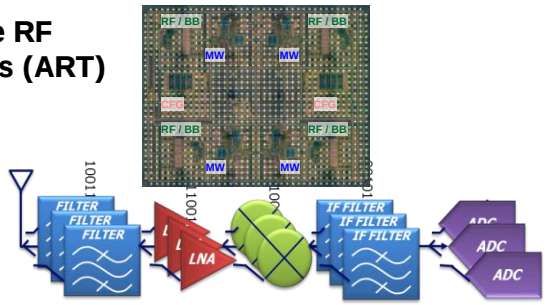
Servers

Storage systems

Storage (short term, long term, temp, fast, slow, etc.)

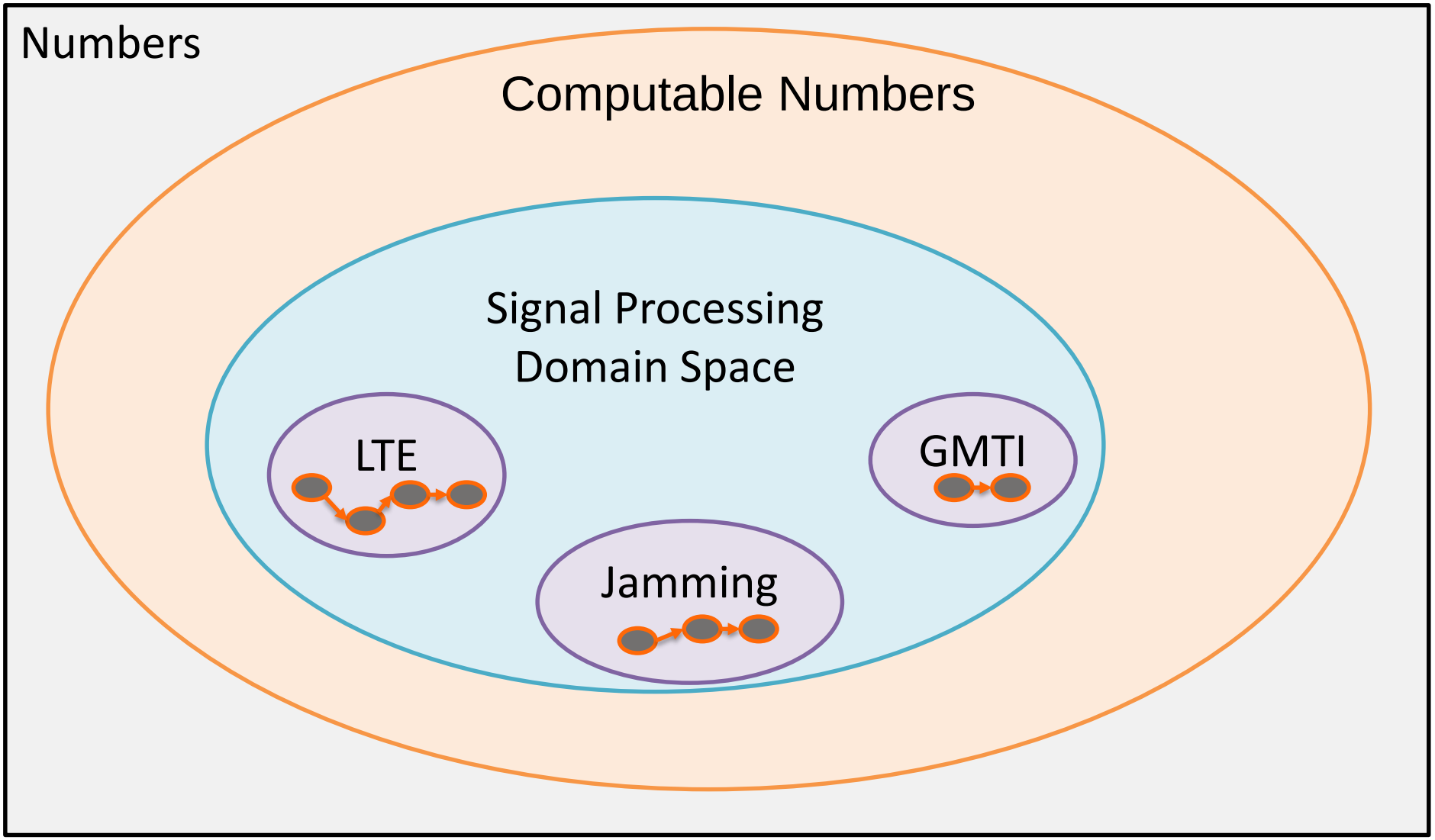
Virtualized RF

Adaptive RF Technologies (ART)

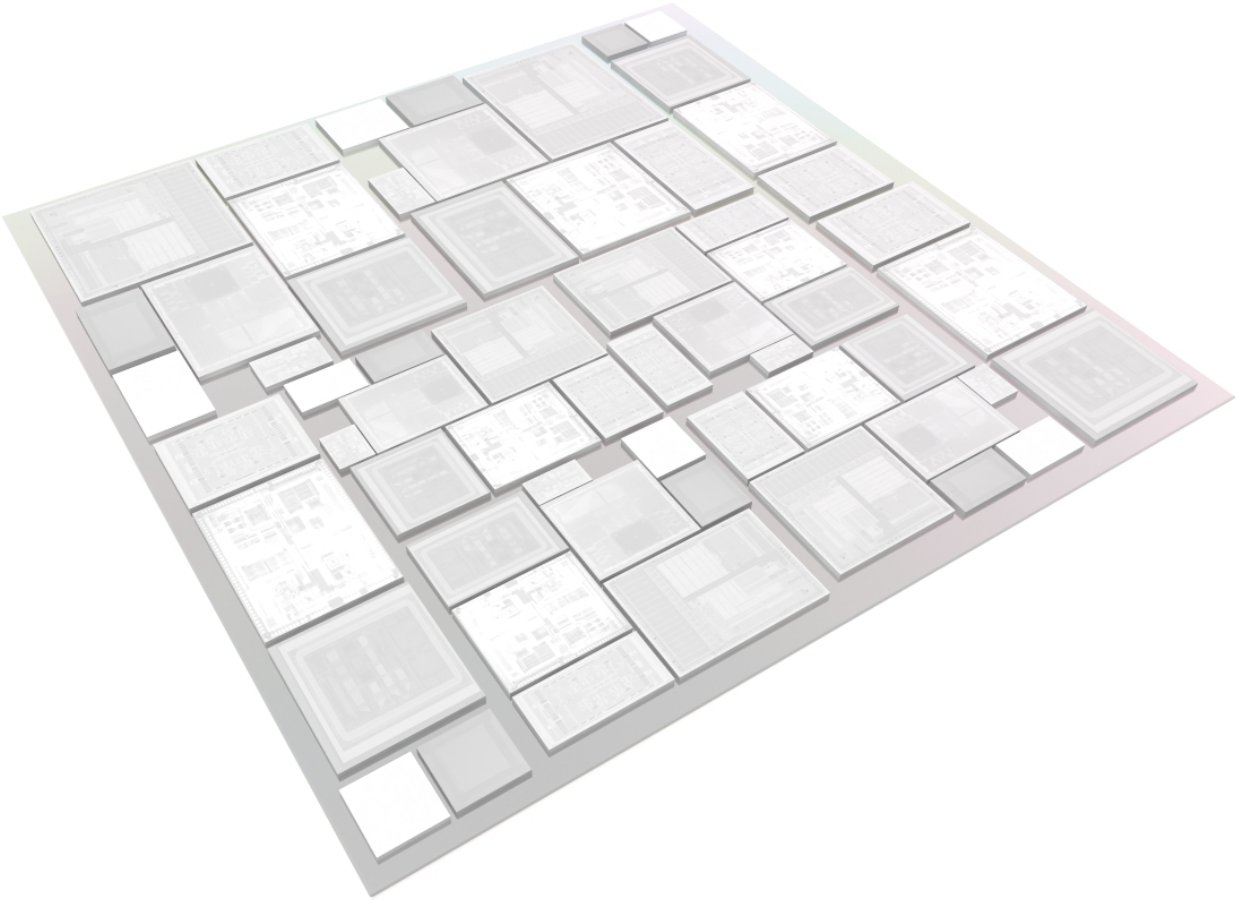


Arrays at Commercial Timescales (ACT)

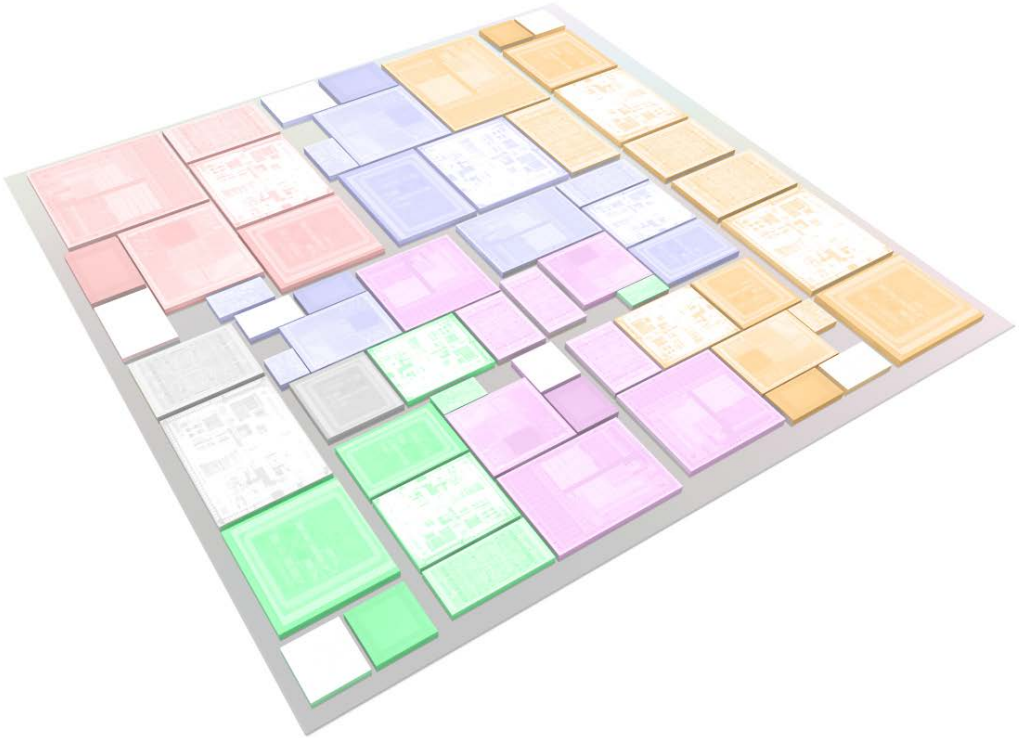
Computable Spaces



Heterogeneous Processing
Domain-Specific System on Chip (DSSoC)



Heterogeneous Processing
Domain-Specific System on Chip (DSSoC)



General Purpose

Graphics Processors

Fourier Transforms

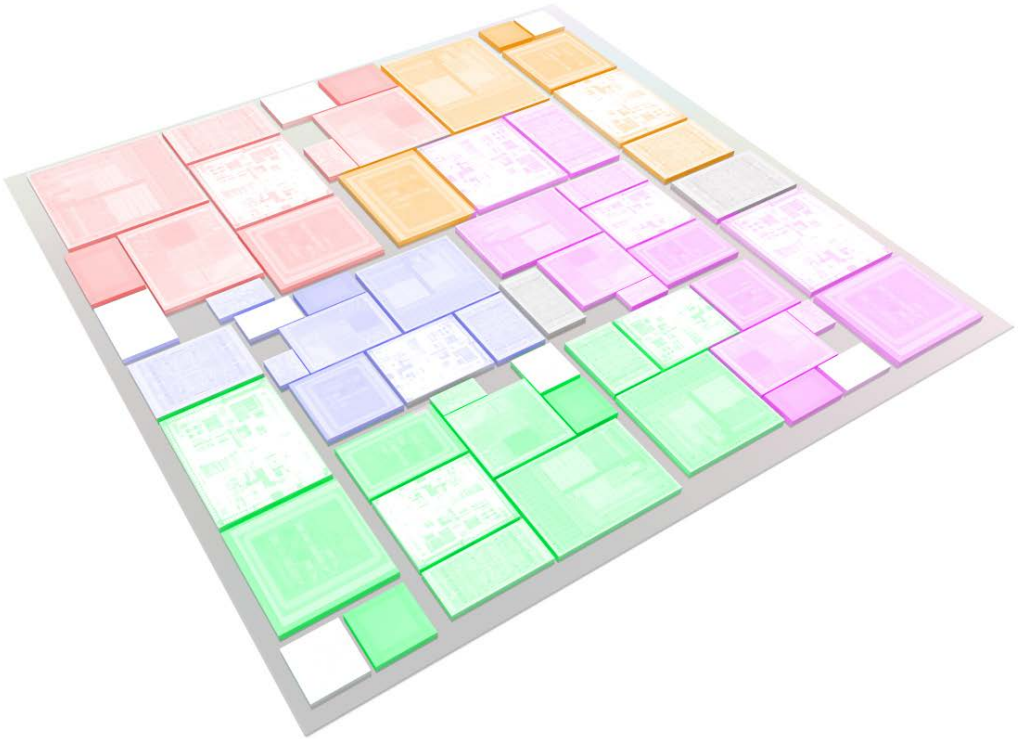
Forward Error Correction

Matrix Multiplier

Others(?)

- Rely on more general purpose processing elements?

Heterogeneous Processing
Domain-Specific System on Chip (DSSoC)



General Purpose

Graphics Processors

Fourier Transforms

Forward Error Correction

Matrix Multiplier

Others(?)

- Or do we use lots of application-specific processors?

Heterogeneous Processing
Domain-Specific System on Chip (DSSoC)

General Purpose

Graphics Processors

Fourier Transforms

Forward Error Correction

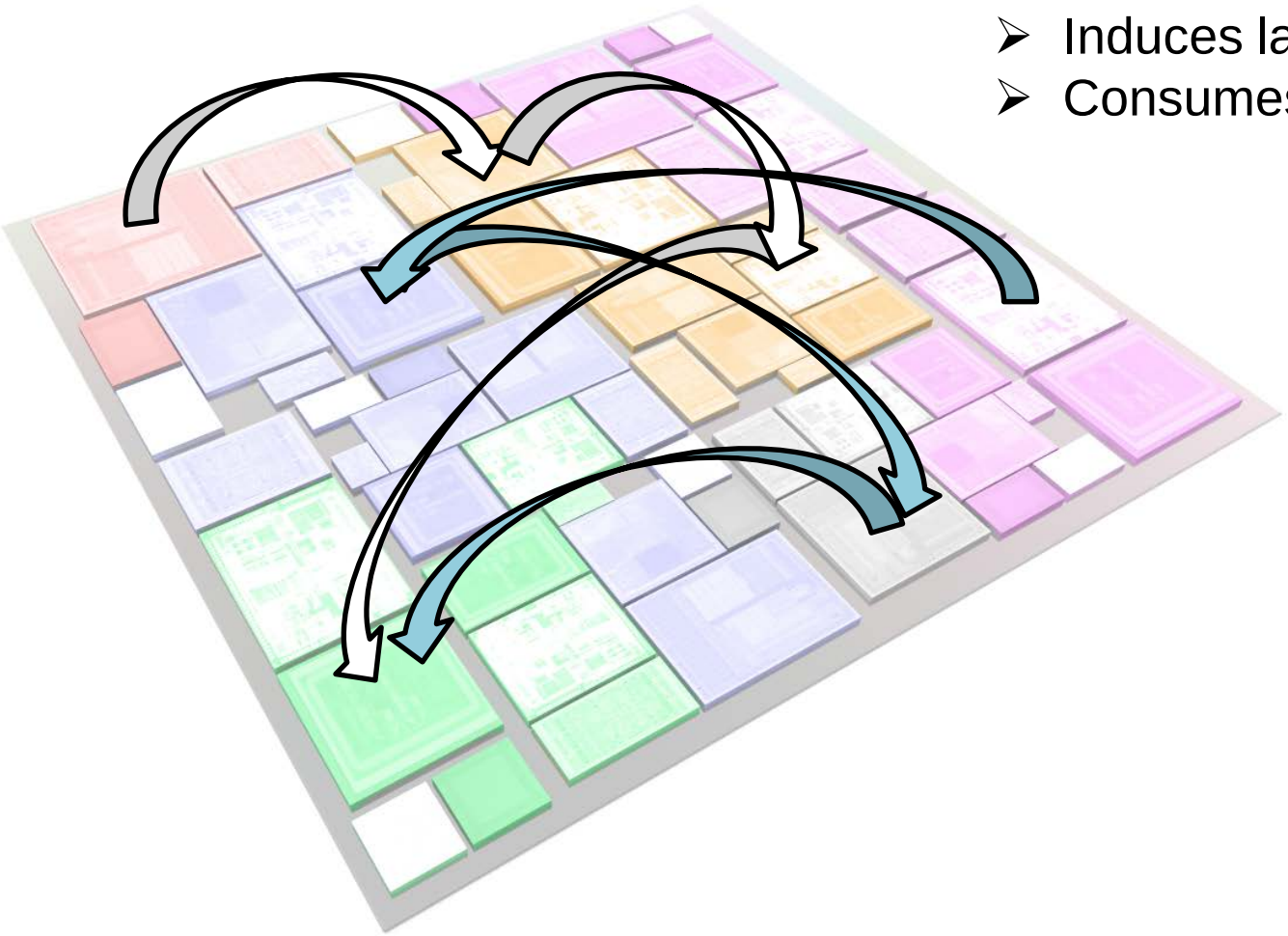
Matrix Multiplier

Others(?)

- Maybe we need hardware-based accelerators?

Supporting Multiple Applications

- Data movement is the enemy
  - Induces latency
  - Consumes power



Impact of Software Ecosystems

Development Tools
Version Control
Continuous Integration
Continuous Deployment
Community Support
Training
Frameworks

Programming Tools
Compilers
Optimizers
Debuggers
Modeling
Simulation
Performance Monitoring

Test and Evaluation Tools
Quality Assurance Testing
Static Analysis
Dynamic Analysis
Closed and Open Loop Testing
Field Experiments

Coordination Tools
Bug trackers
Coding style and guidelines
Examples
Documentation
Contributor Guide

Distribution Statement “A” (Approved for Public Release, Distribution Unlimited)

Seeking ideas in...

- Heterogeneous System on Chip
  - How to determine the number/set of processing elements
  - Scheduling multiple simultaneous apps
  - Power handling/efficiency
  - Etc., etc., etc.

- Software and Programming
  - Tools to write new EM apps
  - Converged RF applications
  - Verification and Evaluation (hardware-in-loop)
  - Etc., etc., etc.

Distribution Statement “A” (Approved for Public Release, Distribution Unlimited)

www.darpa.mil

Systems That Are Alert To Context And Surprise

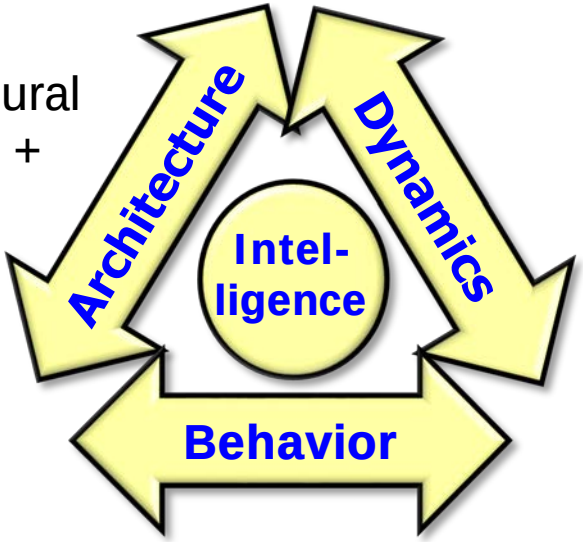
Hava T. Siegelmann
DARPA, MTO

http://www.downloadswallpapers.com/wallpapers/2013/agosto/Papel-de-Parede-golfinho-surfando-na-onda-35733.jpg

Who Am I?

- Joined DARPA 2 Months Ago To Advance AI In MTO
  - Life-long Learning, Context-aware Adaptivity

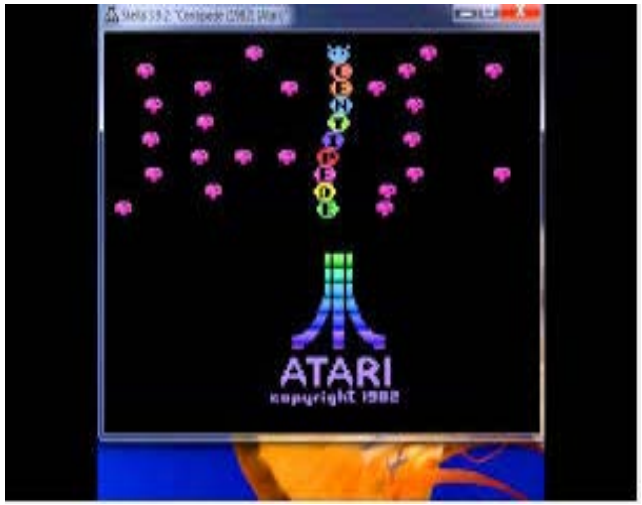
- Came From UMass Amherst: Biologically Inspired Neural And Dynamical Systems (BINDS), Computer Science + Neuroscience And Behavior



- Main Work: Neural Networks, Computational Neuroscience

- Main Contributions In Support Vector Clustering, Analog Recurrent Neural Networks
  - Analog, Turing, And Super-Turing Computation
  - Innovations In Computation, Cognitive, Biological, And Physical Processes

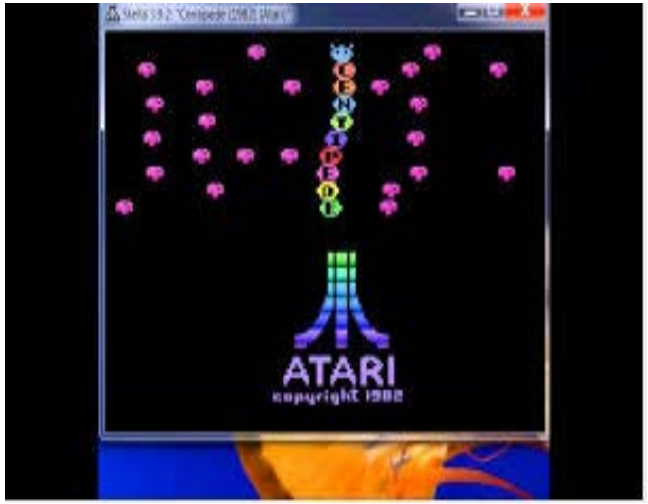
AI Technology



2015:
Google DeepMind Masters Atari

http://ytimg.googleusercontent.com/vi/DtTUTs_3Qf8/mqdefault.jpg

AI Technology



2015:
Google DeepMind Masters Atari

http://ytimg.googleusercontent.com/vi/DtTUTs_3Qf8/mqdefault.jpg

2016:
Google DeepMind Beats AlphaGo Champ

https://4.bp.blogspot.com/-kIo5xZbozxo/VuF_adRRsuI/AAAAAAAAB14/a3foAbMbkTg/s1600/Screenshot_2016-03-10-15-25-03.png

AI Technology

2011:
IBM Watson Wins Jeopardy

http://newswalle.com/wp-content/uploads/9/9476/9476_4_a_determine_together.jpg

2015:
Google DeepMind Masters Atari

http://ytimg.googleusercontent.com/vi/DtTUTs_3Qf8/mqdefault.jpg

2016:
Google DeepMind Beats AlphaGo Champ

https://4.bp.blogspot.com/-kIo5xZbozxo/VuF_adRRsuI/AAAAAAAAB14/a3foAbMbkTg/s1600/Screenshot_2016-03-10-15-25-03.png

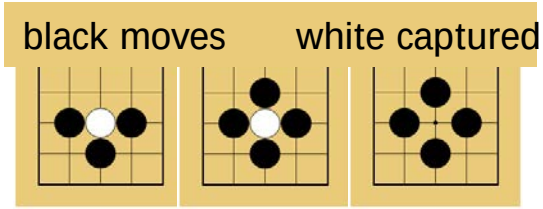
Today's Technology

Great Progress But No Mechanism To Handle Change in Context

- Huge Clusters And Databases
- Clever Programming

- BEST OF 1936's TURING MODEL OF COMPUTATION

- Lacks Flexibility
- Requires Orchestrated Environment



New Rule: surround on diagonals

Network must be completely re-trained

2011
IBM Watson
Wins Jeopardy

2015
Google DeepMind
Masters Atari

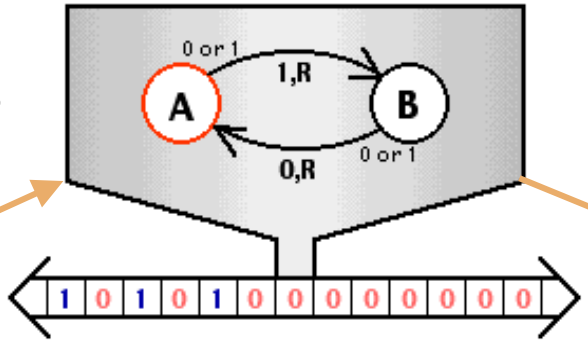
2016
Google DeepMind AlphaGo
Beats Go World Champ

Alan Turing, 1912-1954

1936 "Human-calculators" As Theoretical Automatic Machines

http://2.bp.blogspot.com/-2_iIEWHGey0/VKLLvir2OuI/AAAAAAAALPY/62FByqqVViY/s1600/alan-turing.jpg

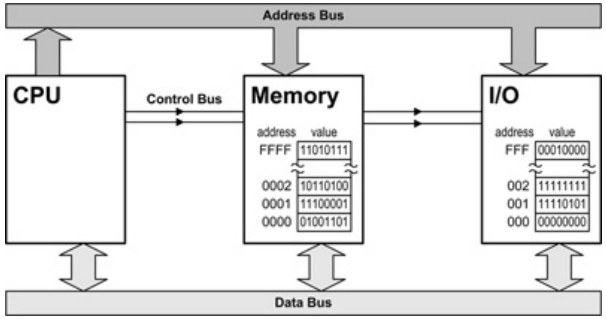
Loadable Program



Input

Memory Tape

Output



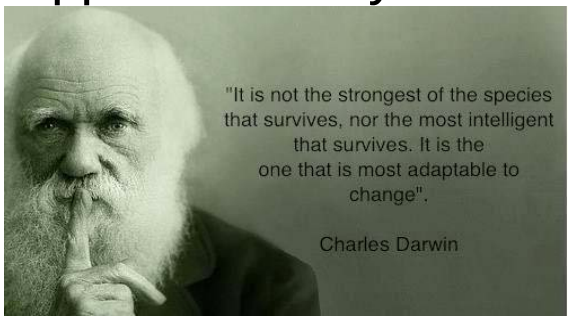
All Current Computers

Current AI Has Two Fixed Parts:

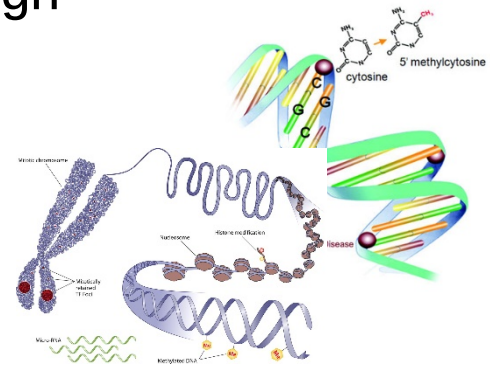
- Parameter Learning (ML)
- Program / Rules

What's Beyond Pre-programming?

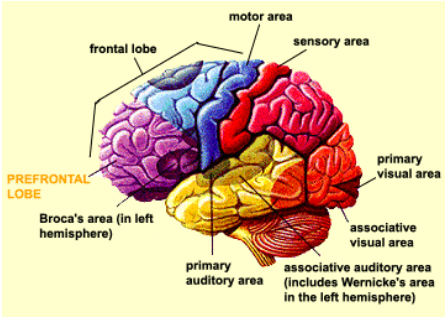
Nature Introduces Agents That Change Themselves To Provide Approaches Beyond Design



https://media.licdn.com/mpr/mpr/AAEAAQAAAAAAAANDAAAAJGMyNDkzMDc2LTg1MGMtNDViNS05N2RmLTdiYjM0M2M1M2NhMw.jpg



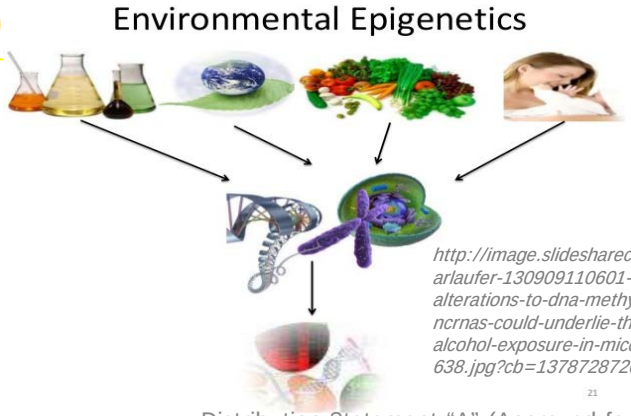
http://2.bp.blogspot.com/-EoTDSv8D_tc/U_eYScuZB_I/AAAAAAAAE58/08xglTNvLh8/s1600/Mechanisms-of-epigenetics.jpg



http://ind3.ccio.co/w3/B9/r1/b54462b246c38979b0288dffa00a186b.jpg?iw=300

Epigenetics

Dynamic Alterations In Cell's Transcription That Affect How Cells Express Genes Result From External/Environmental Factors *(Nature '10)*



http://image.slidesharecdn.com/ipawebinarlaufer-130909110601-/95/longlasting-alterations-to-dna-methylation-and-ncrnas-could-underlie-the-effects-of-fetal-alcohol-exposure-in-mice-21-638.jpg?cb=1378728726

Brain Reconsolidation

Vital Storage Process In Adapting Memories: Memories Can Be Reinforced, Faded, Modified Toward New Experience *(Nature '11)*

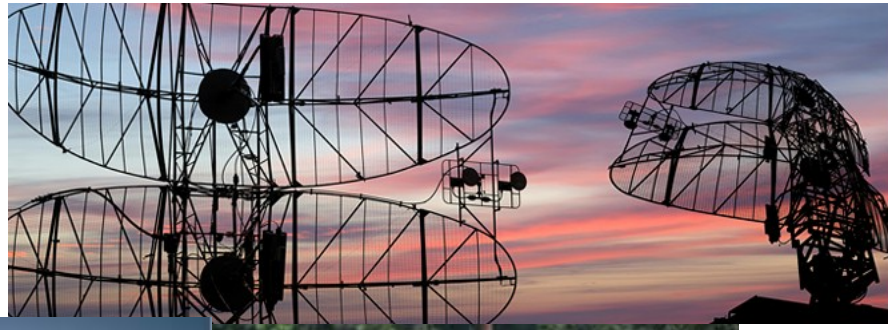
Storage Of Information: Very Dynamic, Temporal Evolution Regulates Behavioral Outcomes

The Holy Grail Of AI: Intelligence Beyond Design

Beyond Pre-programs And Expected Environments

- Flexibility, Adaptivity, Robustness, Efficiency, New Strategies

http://www.tecsignal.com.sa/Images/Products_MainImage/76.PNG



How Can We Reach It ?

http://www.strategic-affairs.com/webmaster/cover_story/images/Creating%20deception.jpg

https://lh3.googleusercontent.com/SS-Z9KCQ59RvPQ8wr_mse40PqiUrdsOPaQS2ha5lOjbIR2O5nSfEsZtp9rnvFPcNxlF3LQ=s128

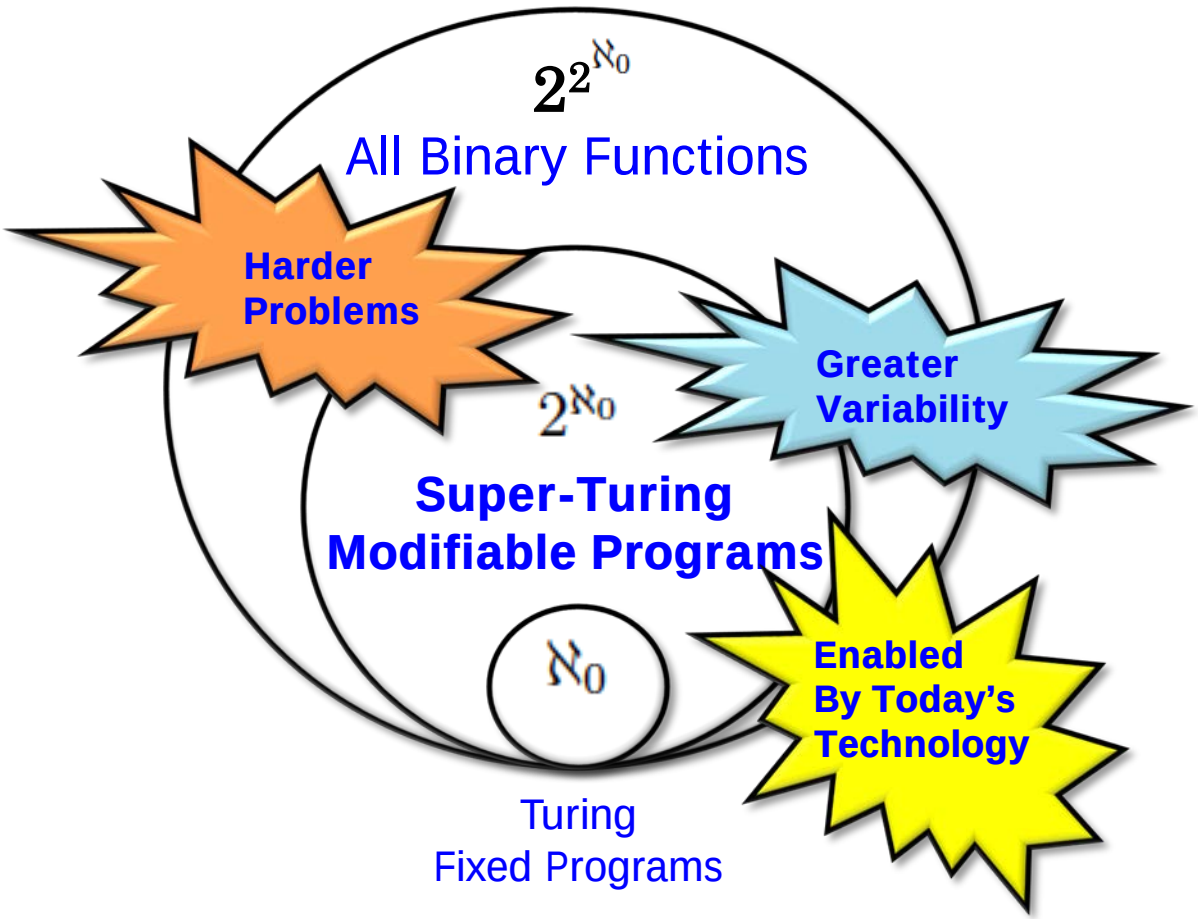
☞ Looking For New Ideas From Cross-Disciplinary Teams To Develop Modifiable Machinery And Enable New Applications

- Mathematics, Algorithms, Biology, Software, Hardware, Materials

Modification → Super-Turing Computation

Modifiable Programs Unlocks A New Computational Class

The Super-Turing Method Is About Acting In The World (Relatively Infinite, Changing, Relatively Random) With Resource Constraints



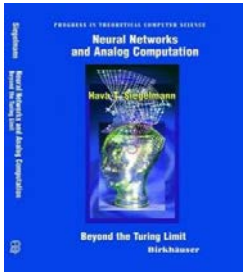
Ingredients

- Evolving, Plasticity
- Randomness/Asynchronous
- Involving Analog Value/Rich Information
- Use Precision/Energy Only As Much As Needed

Technology Enablers

- Recurrent Neural Networks (RNNs)
- Learning Algorithms
- Analog Computing
- Optical Computing

Siegelmann, "Computation Beyond The Turing Limit," Science '95



Turing Didn't Miss It; We Can Build On His Vision

http://totallyhistory.com/wp-content/uploads/2013/07/alan-turing.jpg

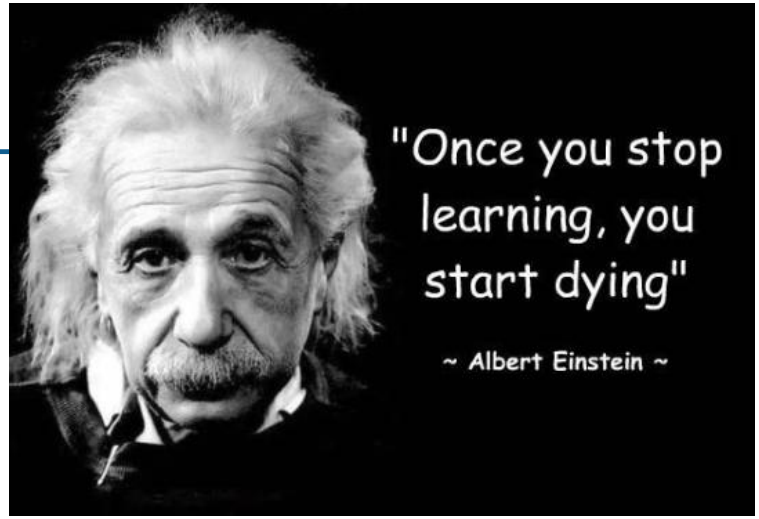
"Electronic computers are intended to carry out any definite rule of thumb process … working in a **disciplined but unintelligent manner**." (Turing '50)

"My contention is that machines can be constructed that will simulate the behaviour of the human mind." (Turing '51)

What May It Enable?

http://www.sidlipsey.com/uploads/2/6/7/9/26794022/8440496_orig.png

Modifiable Augmented Reality



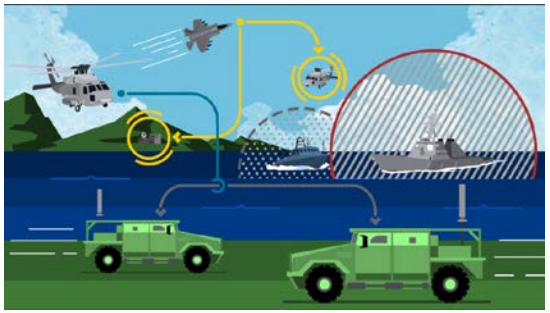
https://qyl.ice.cam.ac.uk/assets/image-cache/media/caseStudies/Quotes/einstein%20c%20Dondy%20Razon%20800px.25575cb6.jpg

http://proactive-pr.com/wp-content/uploads/2016/05/Big-Data.jpg

Accurately Landing Drones

https://lh3.googleusercontent.com/dMeNpn_BGUMwi-2A-4LUAxzP6zDb-pOZlKLbmG8_J9BxmyiSOST1gNaqjmRb74iggwgJ=s127

Adaptive Electronic Warfare



https://www.asdreports.com/media/pr_16653s.jpg

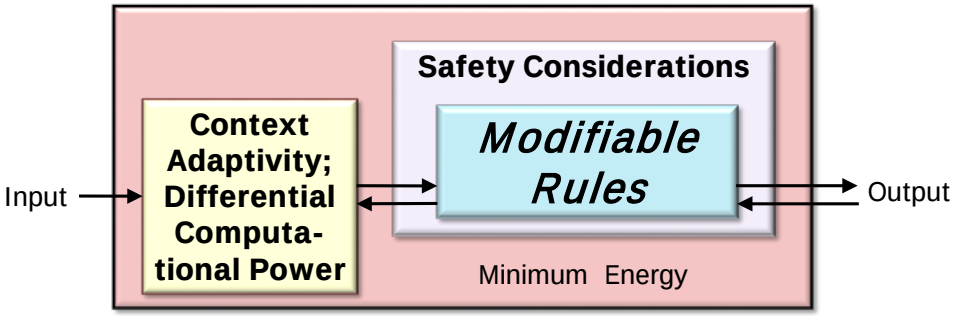
https://lh3.google usercontent.com/XuSIt4CPzTb9FcOJqYe4i31Mgd3TyzC5JJlash37fZtWPjr7mUNW1WEmAeHebIWDZ_OM=s147

Context Dependent Driving In Real Environment

Areas Of Interest

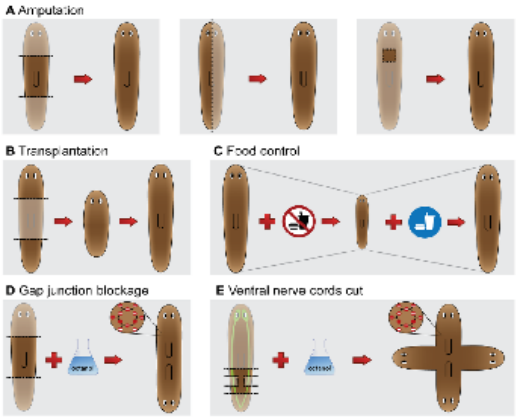
Intelligent Processing

- Life-long Learning: Mitigate Catastrophic Forgetting In Networks
- Contextual Input Processing: Process Inputs Differentially Based on Relevance To Tasks and Goals
- Causal Models That Automatically Modify As New Evidence Arrives
- Initialize Self-modifiable Circuits With Basic Behavior and Capabilities
- Compute With Only As Much Effort/Energy As Necessary In Each Step



Mechanisms of Modification

- Math, Computation, Hardware, Synth Bio: Inspired By Brain / Low Cognition
- Analog (Chemical), Asynchronous, & Recurrent Interconnection



https://www.scienceopen.com/document_file/9e018c4a-8df8-43d6-a3bd-366814bc7cae/PubMedCentral/large.png

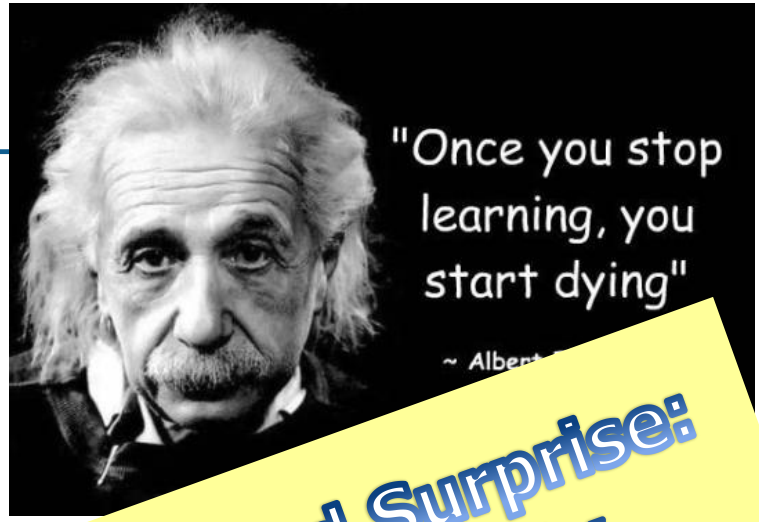
Deployment

- Applications of Impact
- Output Assurance And Security

What May It Enable?

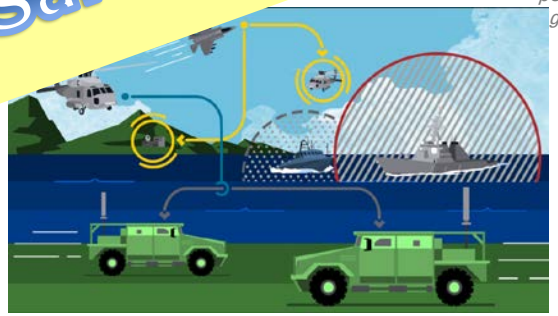
http://www.sidlipsey.com/uploads/2/6/7/9/26794022/8440496_orig.png

Modifiable Augmented Reality



Landing Drones

https://lh3.googleusercontent.com/dMeNpn_BGUMwi-2A-4LUAxzP6zDb-pOZlKLbmG8_J9BxmyiSOSTgNaqjmRb74iggwgJ=s127



https://www.asdreports.com/media/pr_16653s.jpg

Warfare

https://lh3.googleusercontent.com/XuSIt4CPzTb9FcOJqYe4i31Mgd3TyzC5JJlash37fZtWPjr7mUNW1WEmAeHebIWDZ_OM=s147

Context Dependent Driving In Real Environment

Adapt To Defeat Any

Systems That Are Alert To Context And Surprise: Safer AI And Better National Security

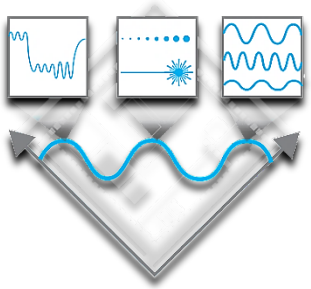
www.darpa.mil

www.darpa.mil

Distribution A: Approved for public release

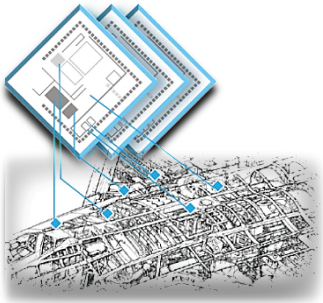
MTO c.2014

EM Spectrum



Operating efficiently in a congested environment while unlocking previously unused portions of the spectrum

Decentralization

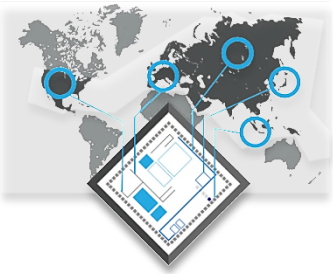


Create a tech base for smaller, less complex systems that together can function as well as a larger entity

Information Microsystems

Enable deep analysis at the tactical edge

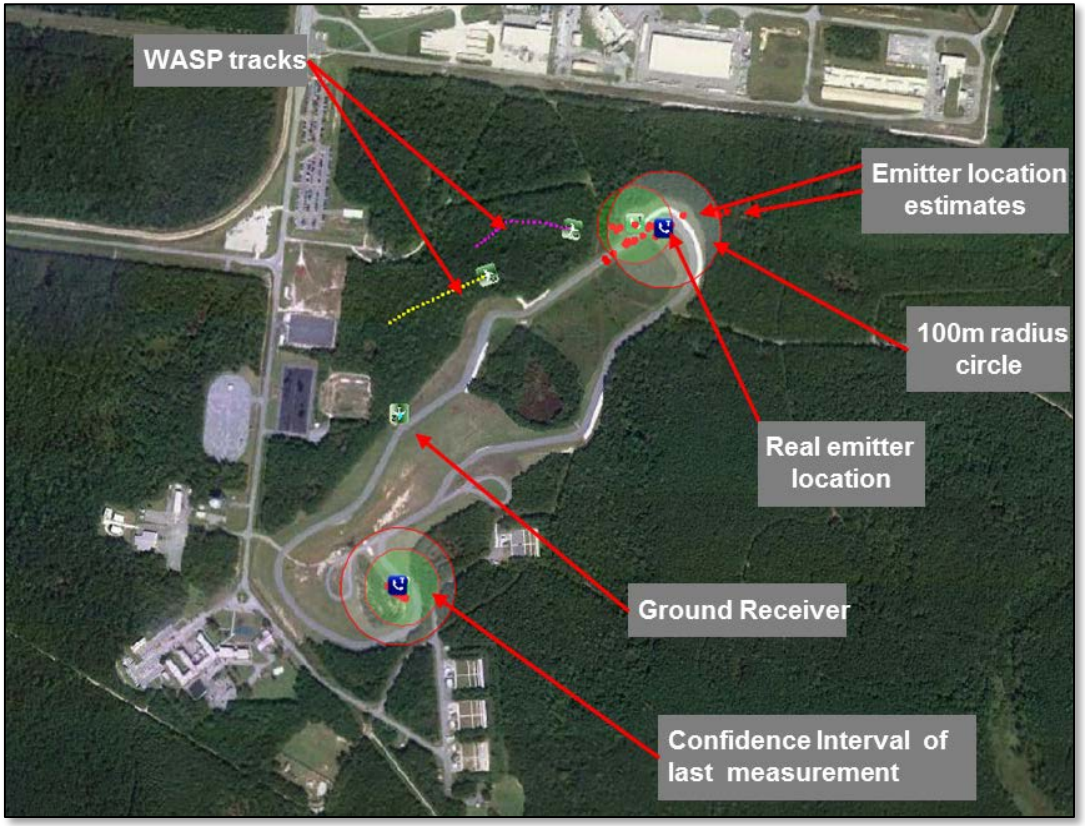
Globalization

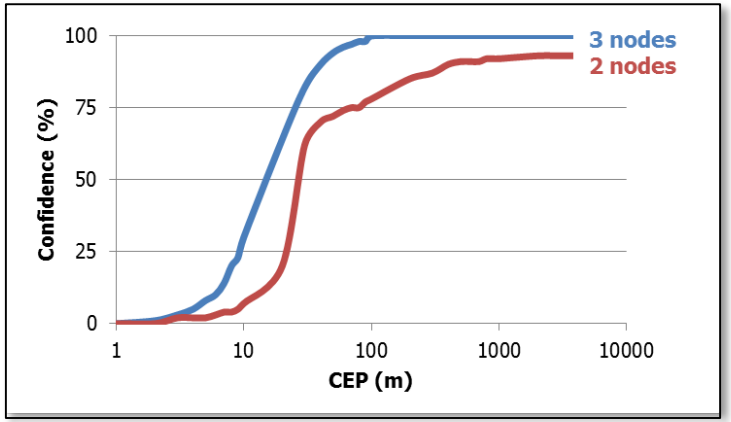


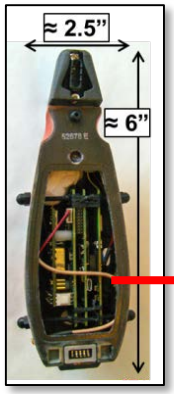
Create a new business model to engage the global electronics market for the DoD

Distribution A: Approved for public release

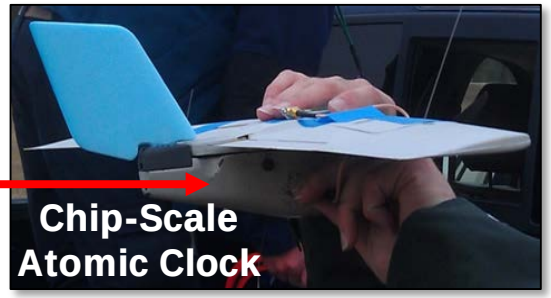
Decentralization: Geolocation using multiple UAVs







WASP Micro-UAV



Distribution A: Approved for public release

www.darpa.mil

Distribution A: Approved for public release

Enabling Next Generation Machine Learning

Trung Tran
Program Manager
Microsystems Technology Office

Proposers Day

September 20, 2016

Distribution A: Approved for public release

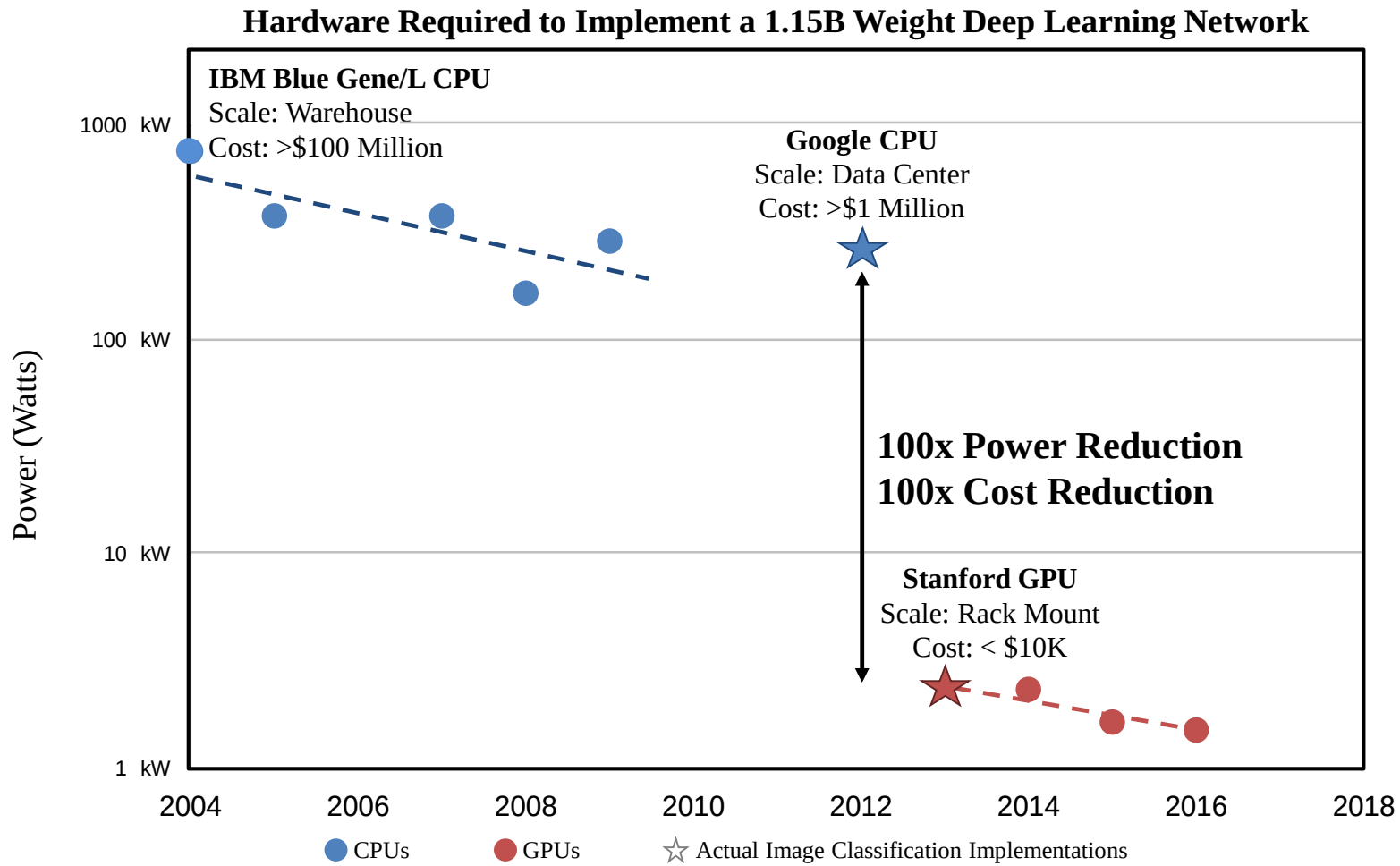
Who am I?

- 1 year at DARPA
- 15 years building processors, cluster computing, and networks in Silicon Valley
- Air Force Academy graduate (6 years active duty)

Goal: To design hardware to enable true artificial intelligence

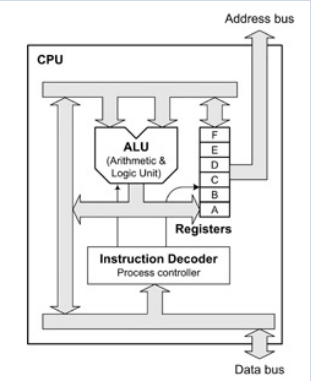
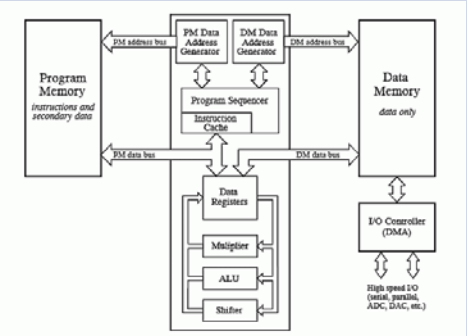
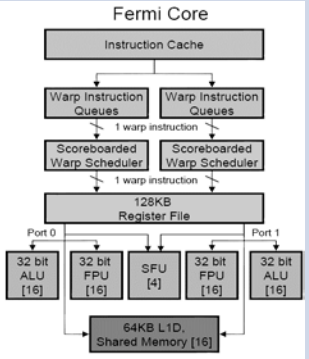
"Machines which can understand and interact with their world"

Hardware has played a vital role in advancing AI



The GPU made Deep Learning functional and accessible by dramatically reducing the cost and processing power relative to CPUs.

Domain specific processing is not a new idea

CPU General math	DSP Signal processing	GPU Graphics rendering
		
1970's	1980's	2000's
Scalar	Scalar	Vector
ALU	ALU+MAC	ALU+MAC+SIMD
Batch	Streaming	Streaming

Artificial Intelligence Research State of the Art

Tool	Result	Class
Stochastic Optimization	How can we achieve the best result including the effects of uncertainty?	Prescriptive Analytics
Optimization	How can we achieve the best result?	
Predictive Modeling	What will happen next it?	Predictive Analytics
Forecasting	What if these trends continue?	
Modeling	What could happen?	
Anomaly Detection	Is action needed?	
Classification	What is the problem?	Descriptive Analytics
Data clustering	How many, how often, where?	
Detection	What happened	

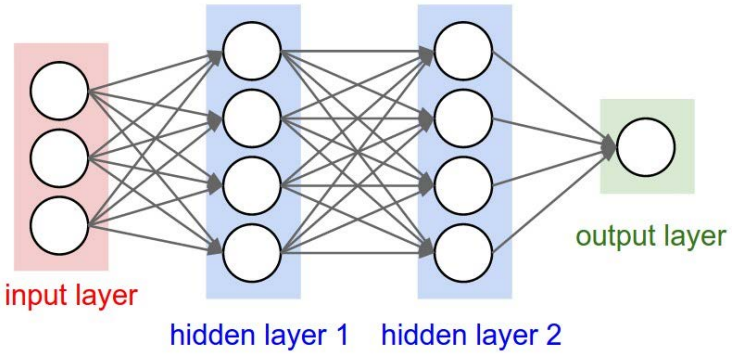
Emerging Research
Probabilistic Programming
Stochastic Optimization
Decision Trees

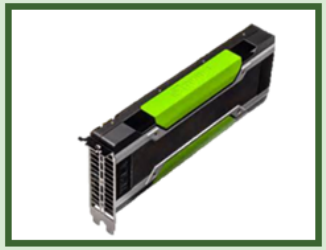
Active Research
Graphical Models
Random Forests
Greedy
Genetic
Reinforcement Learning
Markov Chains

Current Focus
Anomaly detection
DNN classifiers

Specialization is occurring in hardware for AI

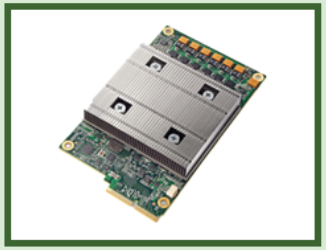
Classification	What is the problem?	**Descriptive Analytics**
Data clustering	How many, how often, where?	
Detection	What happened	





Nvidia GPU

- Parallel processing
- Sequential memory access
- Faster (288GB/s) to memory
- Limited scalability (20GB/s)
- Used for CNNs



Google TPU

- Parallel processing
- Sequential memory access
- Slow (20GB/s) to memory
- Limited scalability (16GB/s)
- Optimized for DNNs

Developing next generation specialization for AI

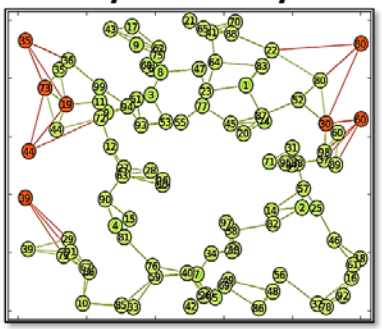
Predictive modeling	What will happen next it?	Predictive Analytics
Forecasting	What if these trends continue?	
Modeling	What could happen?	
Anomaly detection	Is action needed?	

HIVE

- Parallel processing
- Parallel memory access
- Fastest (TB/s) to memory
- Higher scalability (TB/s)
- Optimized for Graphs

HIVE BAA 16-52

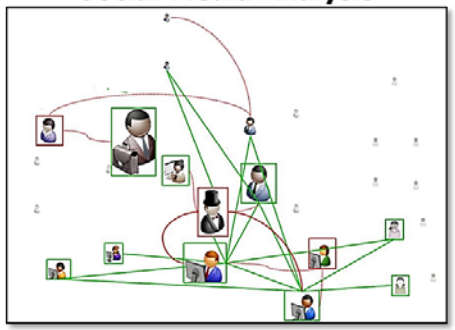
Cyber Security



Which IP events are probes on the network?

- Who are they probing, who have they infected in the network?
- Only a small number of events are probes – graph is sparse.

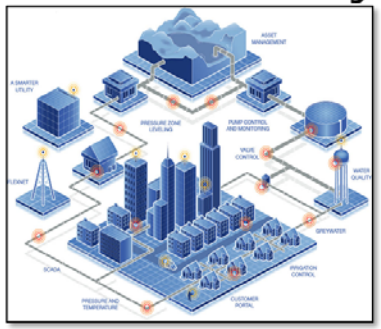
Social Media Analysis



Who influences me to buy a product?

- Who has access to my social media pages, what are they saying to me?
- Since only a few people have direct influence on me – graph is sparse.

Infrastructure Monitoring



Can I spot failures before they become critical?

- How do I avoid cascading failures and what are the system dependencies?
- Only a small number of critical dependencies – graph is sparse.

Graph analytics is beginning to be applied to a broad set of problems

Going beyond the possible

Stochastic Optimization	How can we achieve the best result including the effects of uncertainty?	**Prescriptive Analytics**
Optimization	How can we achieve the best result?	

Goal to **create a probabilistic processor that calculates probability distribution functions in real time**

- Enabling development of adaptive & predictive models which allow us to interpret events based on what we expect to happen

$$E(X) = \Sigma(p_i \times x_i)$$

Model of what we expect

Is a function of it's features times the probability that those features are correct

The problem with hardware today

	Digital static normalized	Probabilities are analog and vary over time	In order to process the math
	Data-based quantity	**Equivalent mathematical quantity**	**limit as n→∞**
	Relative frequency of x_i $\hat{p}_i = f_i / n$	Probability that **X**= x_i, Pr(**X**=x_i) p_i	$\hat{p}_i \to p_i$
	Mean $\bar{x} = \frac{1}{n}\sum f_i x_i$	Expected value of **X**, E(X) $\mu = \sum p_i x_i$	$\bar{x} \to \mu$
	Variance $s^2 = \frac{1}{n-1}\sum f_i (x_i - \bar{x})^2$	Variance of **X**, Var(X) $\sigma^2 = \sum p_i (x_i - \mu)^2$	$s^2 \to \sigma^2$

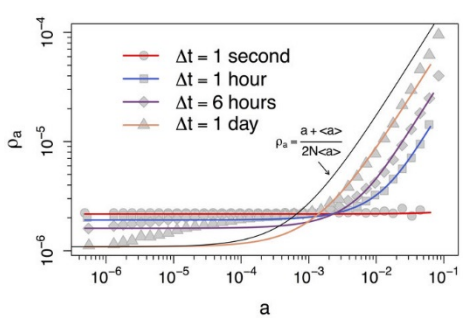
<u>Processors</u> represent uncertainty as Gaussian with a mean and variance

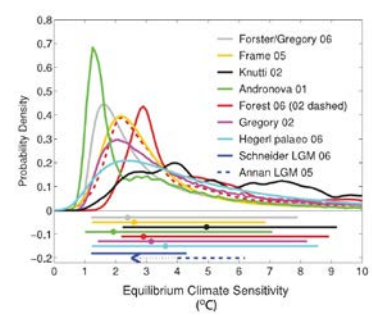
<u>Huge Assumption</u> rely on large sample sets so probabilities normalize.

In the real world: data varies, **<u>probabilities shift</u>**, answers need to be in real time

$E(X) = \Sigma(p_i \times x_i)$ or in neural networks $\Sigma(w_i \times n_i)$

p_i varies with time



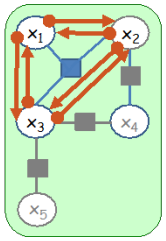


p_i is noisy and not Gaussian

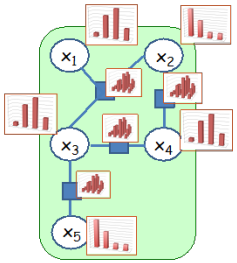
The three challenges

- Challenge #1: Storing a continuous time varying signal
  - Analog vs digital (SNR vs Quantization error)
- Challenge #2: Identifying and modulating the probability distribution function (PDF)
  - PDF = Sum of Gaussians? If so how many and which features to track/measure
  - How do you update PDF based on measured (observed) data
  - How to deal with outliers and aging data which skew distribution
  - Sampling window?
- Challenge #3: Converting the PDF to a decision
  - Sampling the distribution for decision trees
  - Convex optimization (local minima) for decisions on best available data

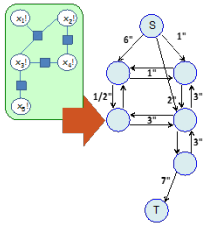
May require new approaches



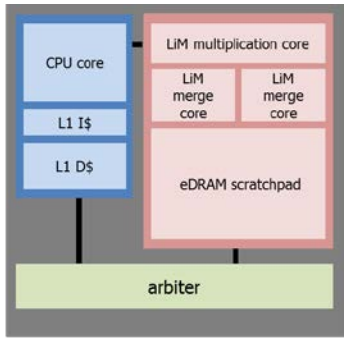
Belief Propagation



Sampling
(Gibbs, MCMC, etc)



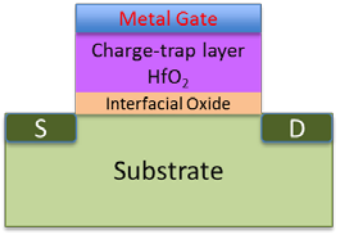
Graph Cuts
(→ Network Flow)

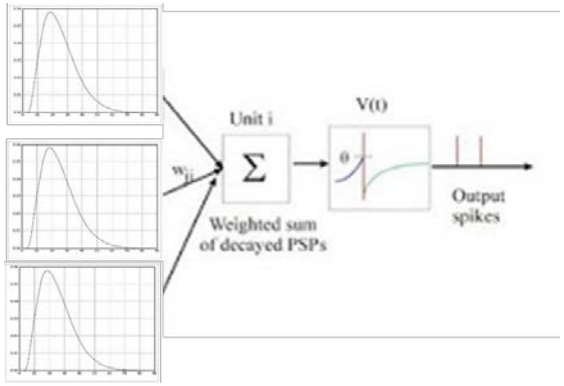


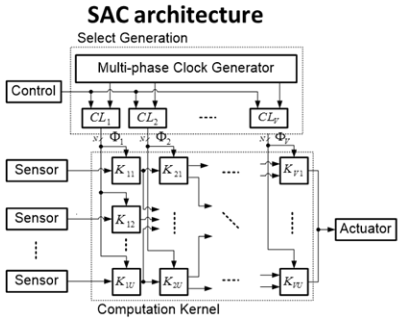
New Architectures

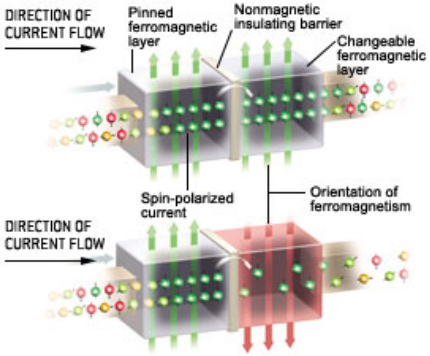
New Materials

High-k HfO_2 charge-trap









New Circuits

www.darpa.mil

“In Hardware We Trust”

Mr. Kerry Bernstein
Program Manager
Microsystems Technology Office

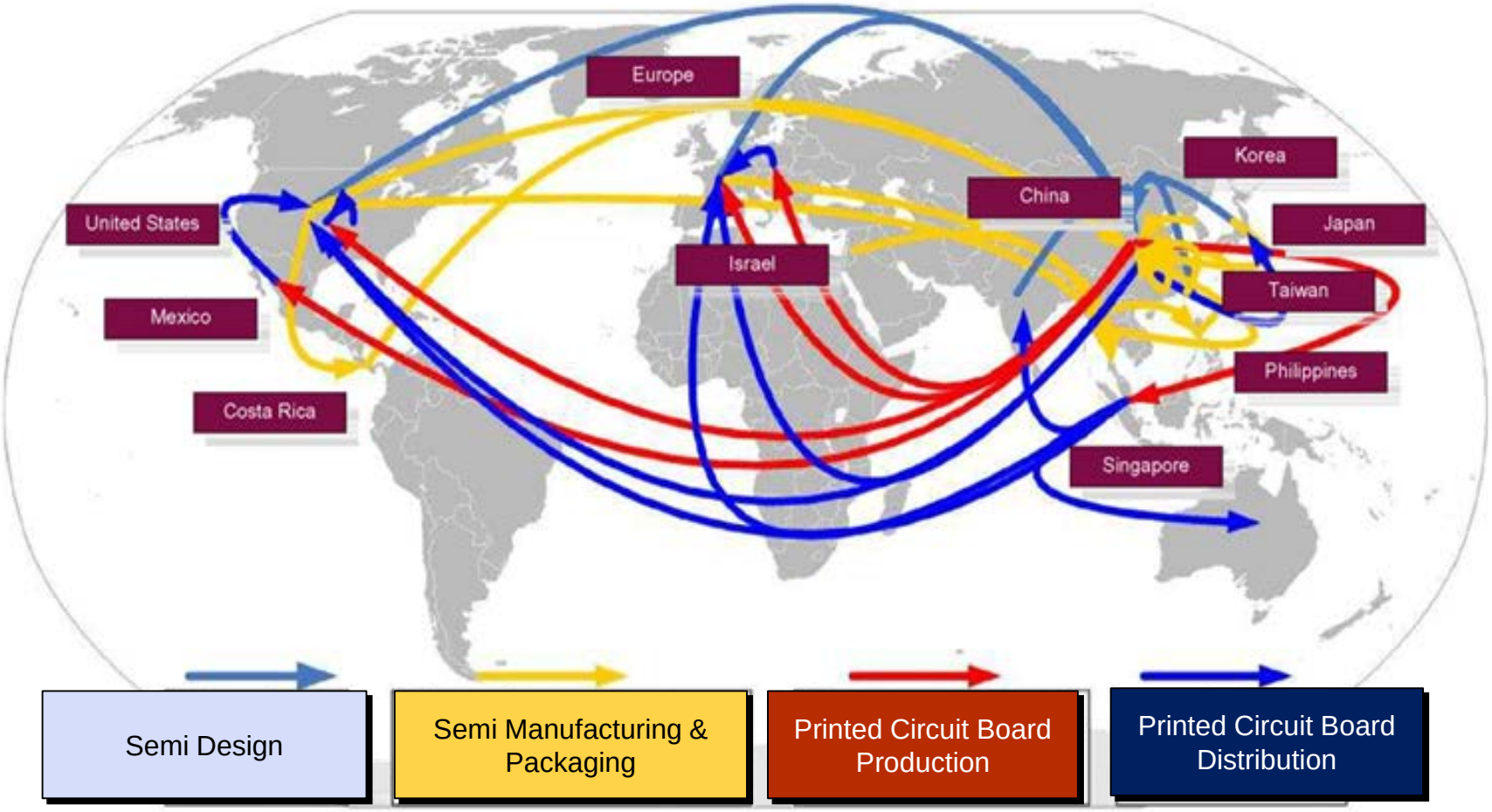
Proposers Day

September 20, 2016

Distribution A: Approved for public release

The Global Nature of Today's Supply Chains

Global nature of supply chain makes "chain-of-custody" protection unworkable

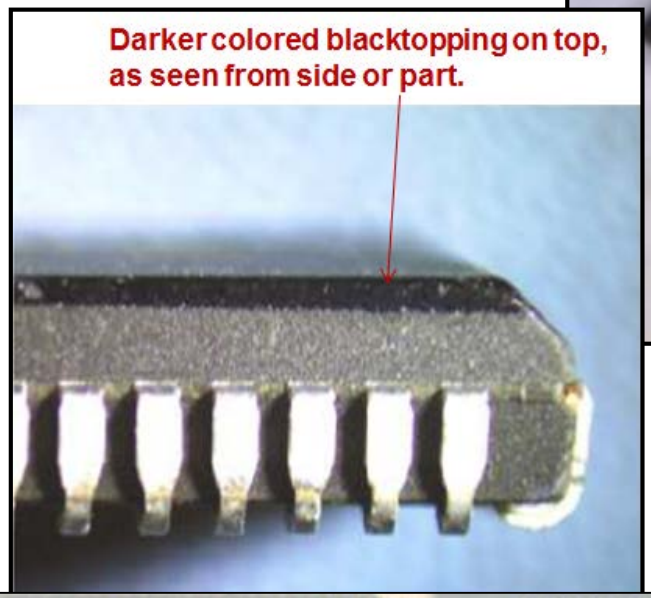


Source: IDC Manufacturing Insights & Booz Allen analysis

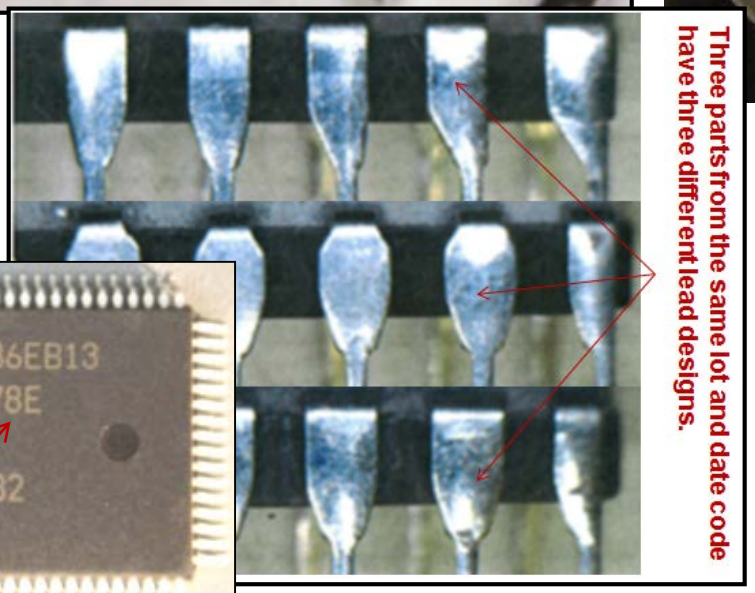
Lifecycle shown for a single JSF component
– Component changes hands 15 times before final installation

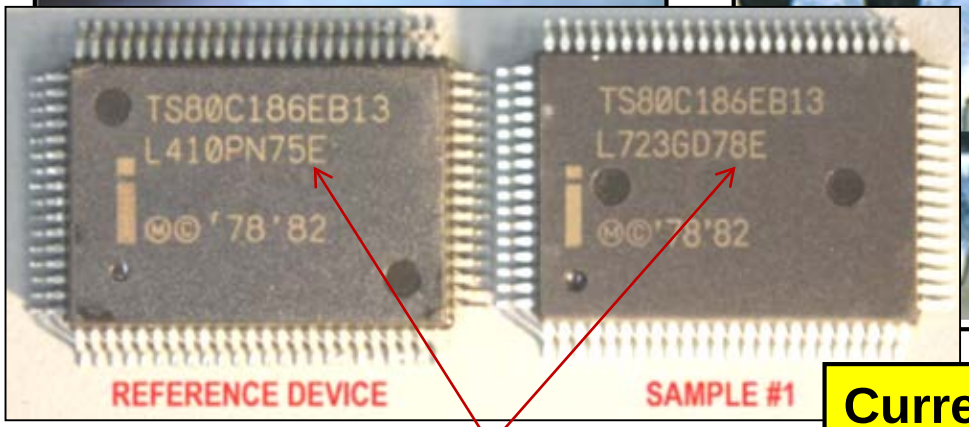
Distribution Statement A, Approved for Unlimited Distribution

Current Counterfeit Detection is Inspection-based



This device last shipped in 2004. '0724' means the 24th week of 2007, over two years after the last ship date.





Lot L723GD78E does not exist, according to Intel (manufacturer). Other font/cavity/logo differences exist.

Current techniques find only the most fundamental of exploits; counterfeits routinely infiltrate our supply chain

All images courtesy of MDA

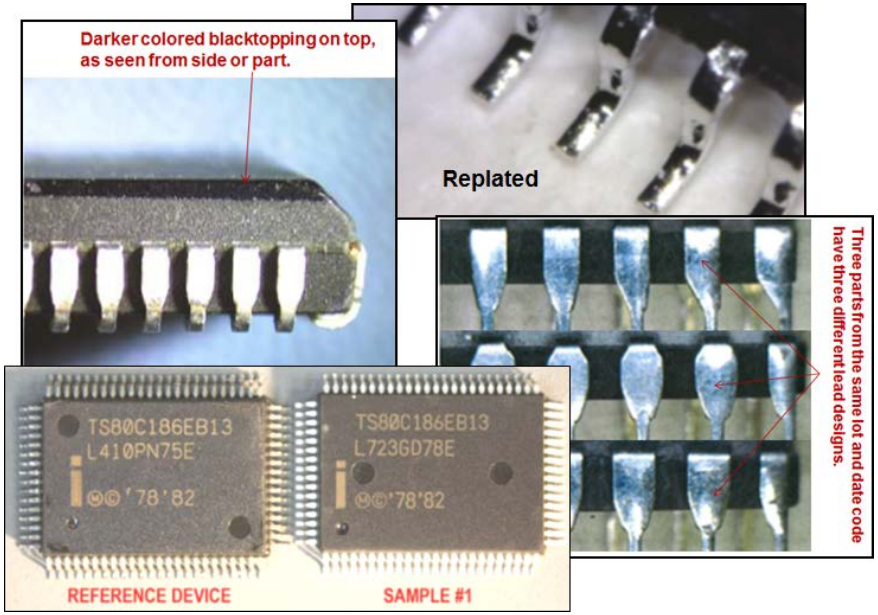
Distribution Statement A, Approved for Unlimited Distribution

Counterfeits vs Clones

Counterfeits

Still the original part from OEM:

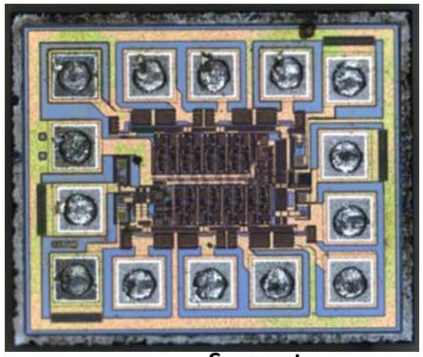
- Recycled used components
- OEM's fab test failures sold on black market.
- Unlicensed fab overproduction



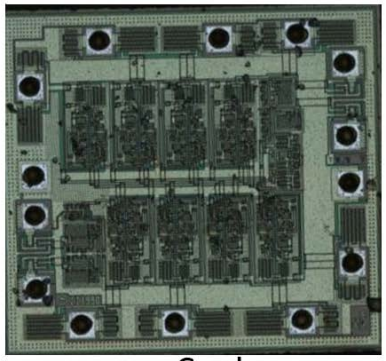
Clones

A completely different part:

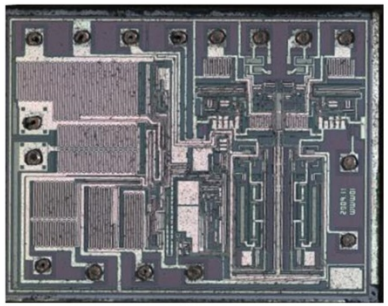
- Copies fabbed in foreign plant
- New design of reverse-engineered components using stolen IP, potentially with altered function



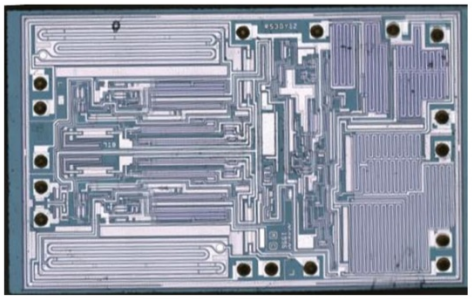
Suspect



Good



Suspect

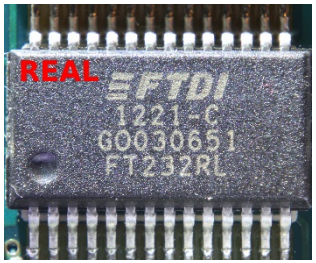


Good

Distribution Statement A, Approved for Unlimited Distribution

All images courtesy of NSWC CRANE

Future Technology Devices International: The consequences of counterfeit electronics



FTDI USB to Serial Converter Integrated Circuit

- The most popular USB to Serial Conversion chip on the market
- Ubiquitously used: Arduino™ boards (700,000 registered users), consumer products, microcontrollers, PCs, prototyping

Fake versions of FTDI chip

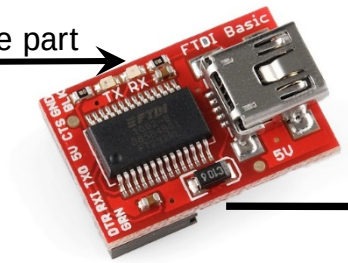
- Counterfeits / clones are common; run FTDI's proprietary driver SW
- Customers unwittingly buy legitimate boards with fake FTDI chips

FTDI modified software drivers "brick" hardware when a fake chip is detected

- Frustrated, innocent customers wound up with useless hardware
- FTDI alienated users while trying to protect their IP

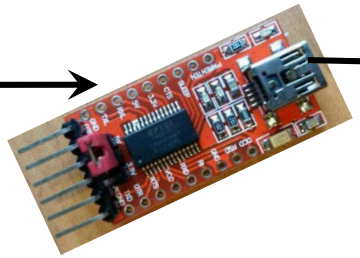
FTDI
USB-RS232
RS485/RS422

Legitimate part



Good product

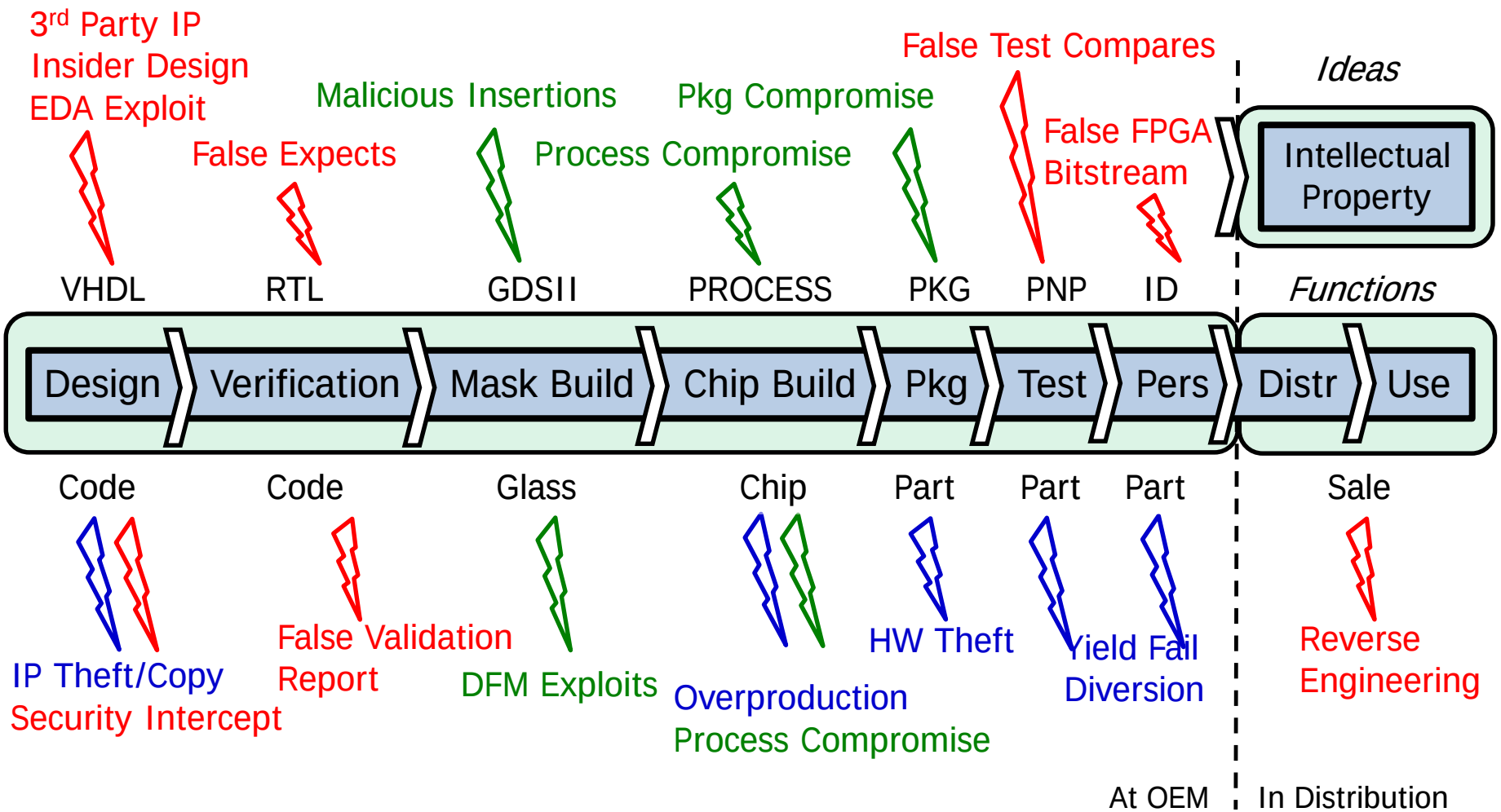
Counterfeit part



Questionable

Hardware-specific Exploits, Mitigations

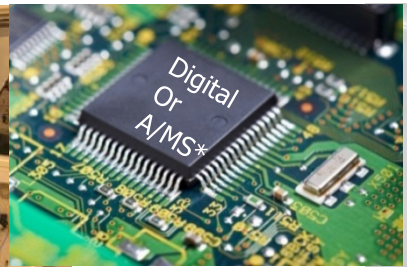
LEGEND: Design Attack - Hardware Attack - Logistics Attack



Distribution Statement A, Approved for Unlimited Distribution

DARPA MTO Hardware Security Programs

Trust tools | IRIS Test Articles | Vanishing circuits | Was it really built here? | SHIELD Dielet



2007 2008 2009 2010 2011 2012 2013 2014 2015 2016

Hardware Functionality

TRUST

Reliability Checking — IRIS

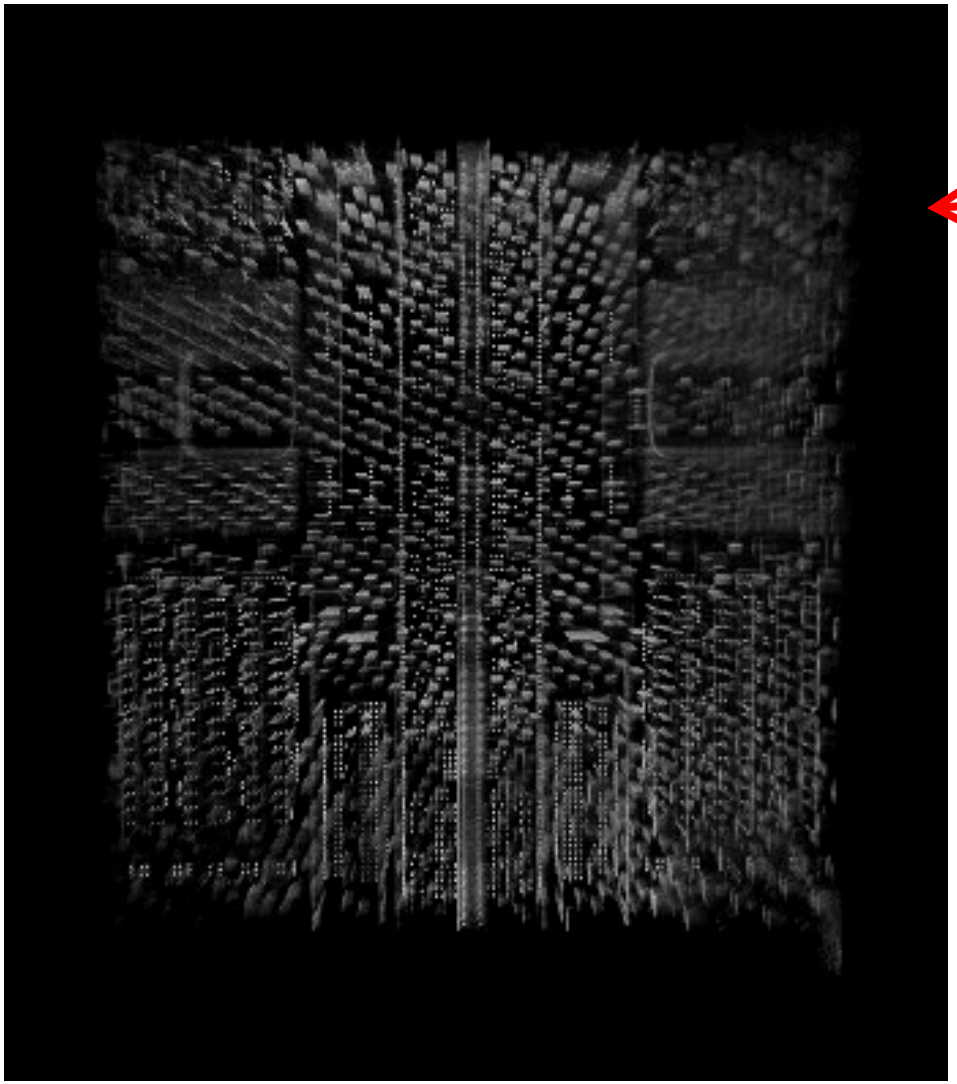
"Vanishing" Circuits — VAPR

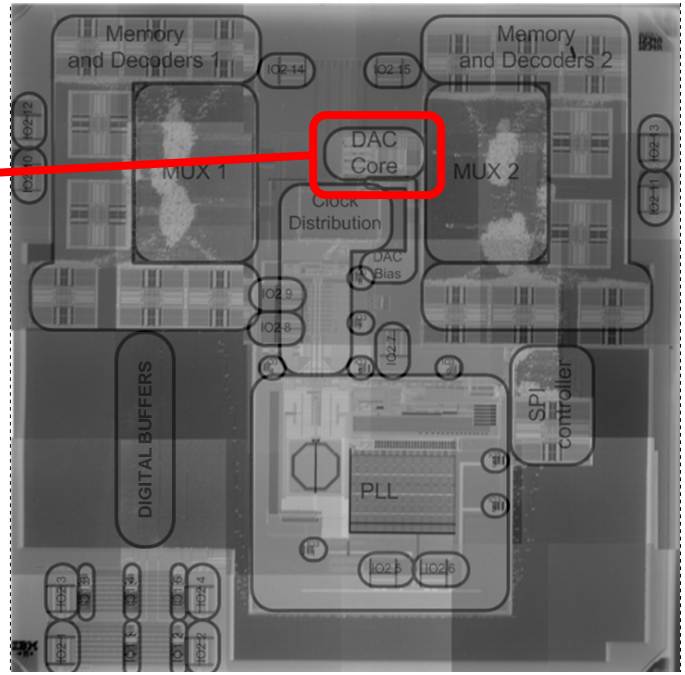
Unique Fab Signatures — Fab-of-Origin

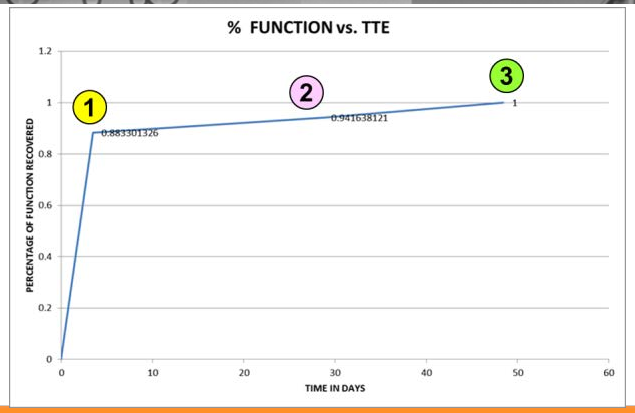
Supply Chain Security — SHIELD

Distribution Statement A, Approved for Unlimited Distribution

3D Reconstruction of DAC - Non Destructive



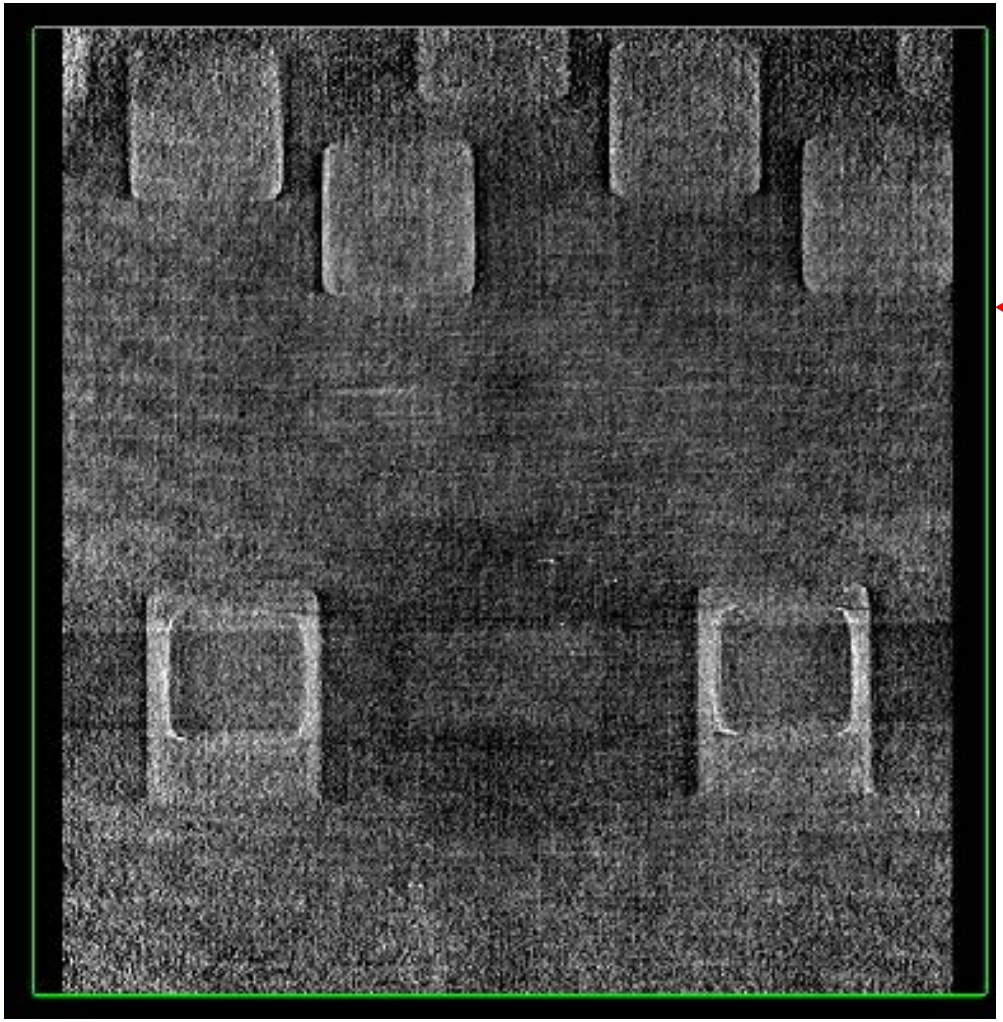


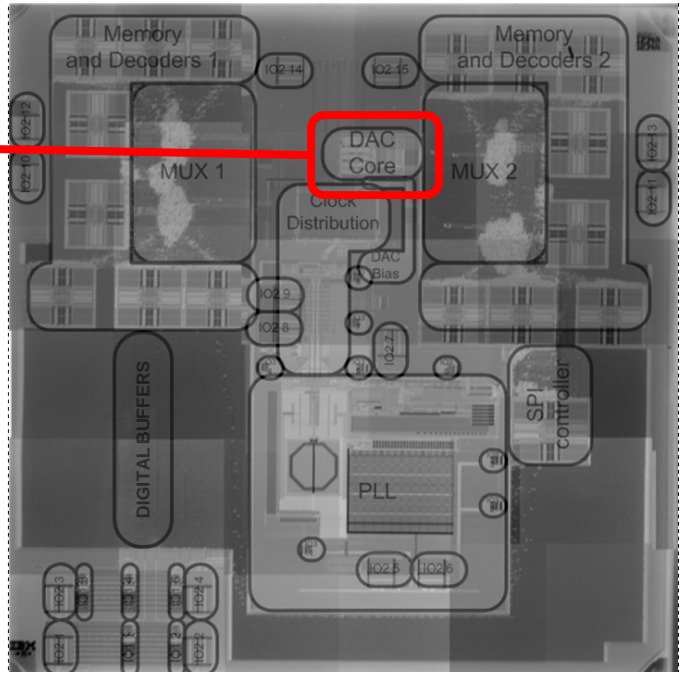


ENABLES 3D VISUALIZATION AND SPATIAL ANALYSIS

Distribution Statement A, Approved for Unlimited Distribution

Layer Extraction on DAC



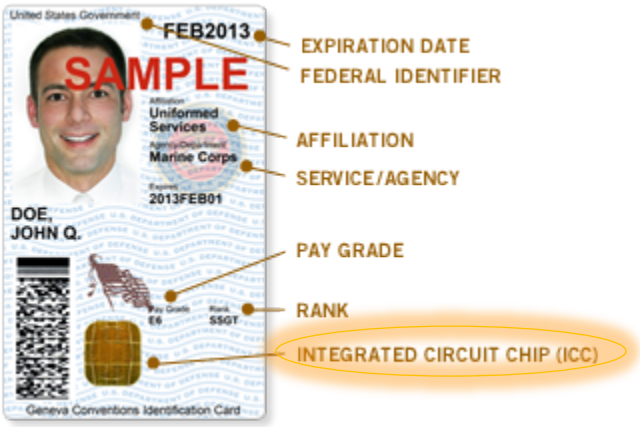


HIGH RESOLUTION IN DEPTH ENABLES LAYER SEPARATION AND MEASUREMENT OF THICKNESS WITHOUT GRINDING

Distribution Statement A, Approved for Unlimited Distribution

A Hardware Root of Trust for Integrated Circuits

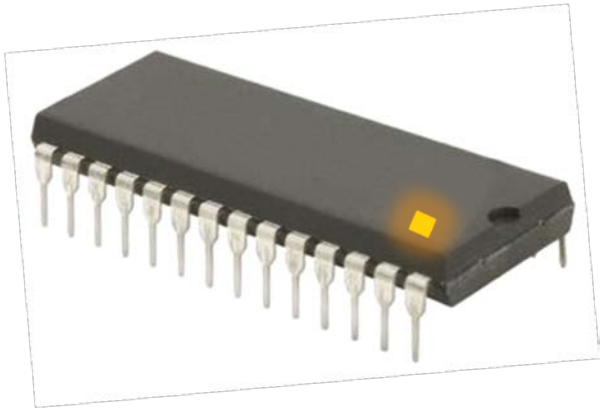
Apply RFID chip concept...



Common Access Card

- PIN (known only to card holder)
- ID Certificates

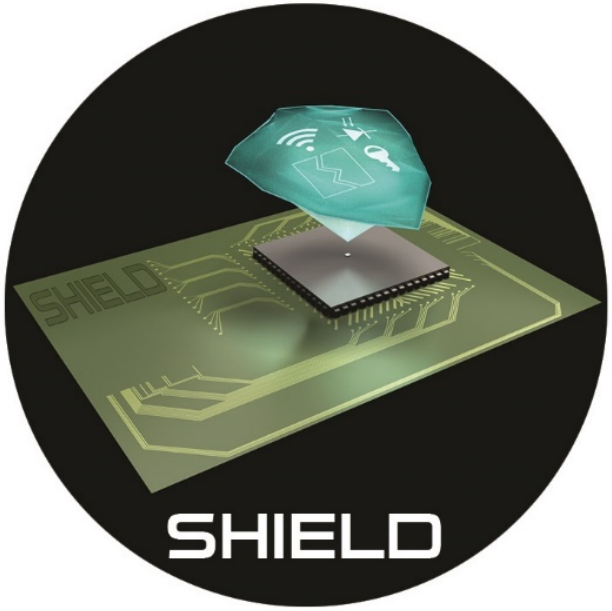
...to integrated circuit integrity



SHIELD Dielet

- Onboard encryption engine with secret key (does not transmit)
- Serial ID

SHIELD: DARPA's Supply Chain Solution



0.1mm x 0.1mm
10 microns thick

100K transistors
(14nm CMOS)

50 µW total power

Passive sensors to detect tamper attempts

Designed-in fragility to thwart dielet removal

256 bit encryption engine

< $0.01 per dielet

No impact to host IC

SHIELD dielet surrogate placed on a penny.
Image courtesy of Northrop Grumman.

The SHIELD dielet, installed in the package of the integrated circuit, will provide 100% assurance against most common supply chain threats. Physically fragile with on-board industry standard encryption, SHIELD will be highly resistant to cloning and spoofing attempts.

SHIELD makes counterfeiting too expensive and too hard to do.

Distribution Statement A, Approved for Unlimited Distribution

The DARPA HW Security Vision

Goal: Assure the Integrity, Protection of Critical Components used in DoD systems.

- Part does no more, no less than it is supposed to;
- Part does this for its full stated lifetime;
- Part was built where and when it claims to be;
- IP expressed by the part is protected and controlled;
- Component has not been compromised after it leaves OEM;
- Chain of Custody is automated and accountable;
- Capability does not significantly impact cost, performance, power
- Capability does not bind DoD to one sole supplier or fab

➢ Mission readiness requires security as well as reliability
➢ DoD HW must exhibit asymmetric security advantage

http://s.hswstatic.com/gif/combination-lock-ch.jpg

www.darpa.mil

Tales of Emerging Devices

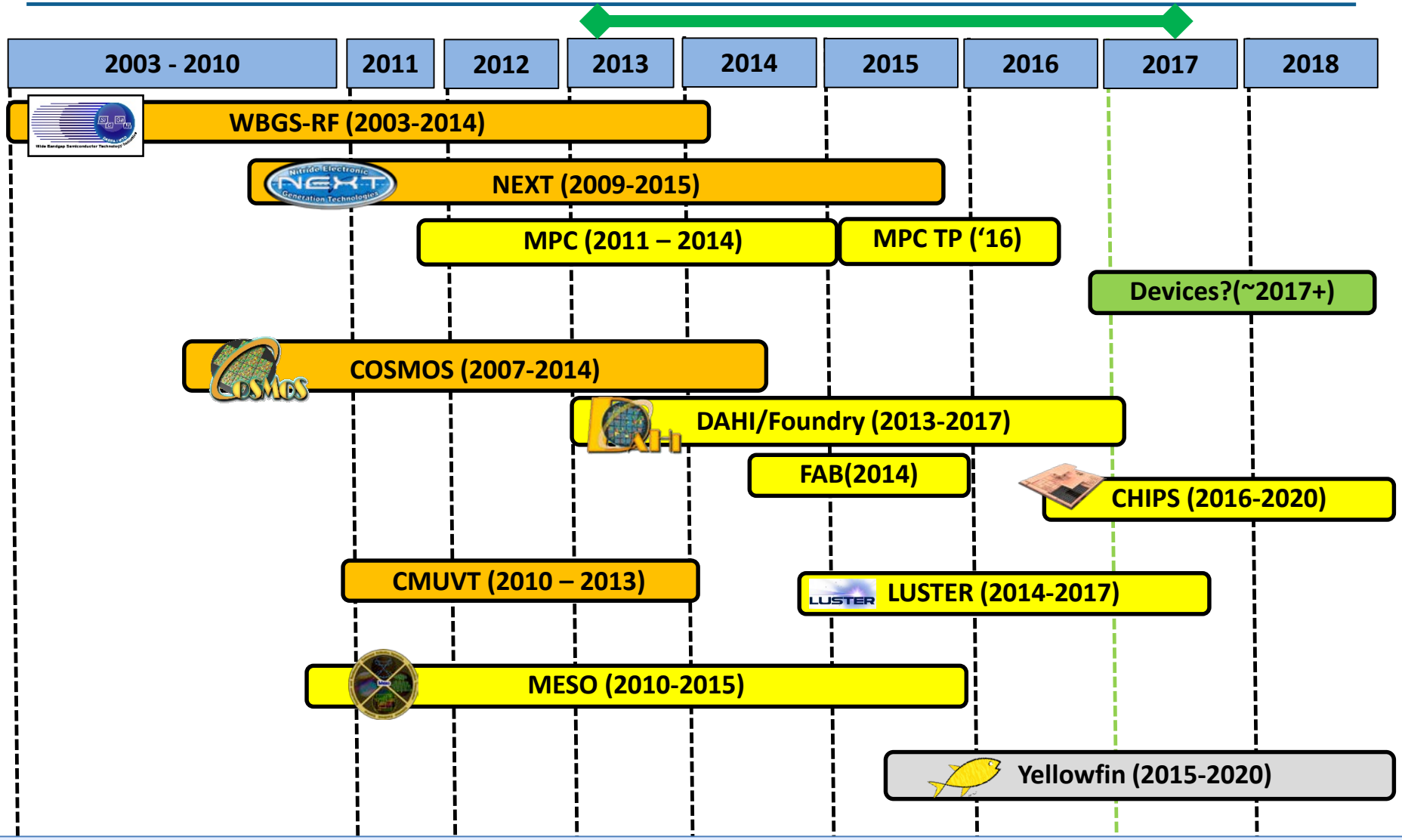
Dr. Daniel S. Green
Program Manager
Microsystems Technology Office

Proposers Day

September 20, 2016

Distribution A: Approved for public release

Green Program Timeline



Thank you!

A Tale of Two Transistors

Si

?

III

V

Data source: https://en.wikipedia.org/

Materials drive electronic performance

← device materials → integration

Parameter	Why?	Unit	Si	GaAs	InP[1]	GaN[2]	COSMOS / DAHI
Electron Mobility	Carrier velocity	10^3 cm²/V·s	1.4	8.5	12	<1	InP
V_{peak}	Transit time	10^7 cm/s	1	2	2.5	2.5	InP / GaN
E_{BK}	Voltage swing	10^5 V/cm	5.7	6.4	4	40	GaN
E_g	Charge density	eV	1.12	1.42	0.74	3.4	GaN
κ	Heat removal	W/cm·K	1.3	0.5	0.05	2.9	GaN / Si
Maturity	Circuit complexity		Excellent	Good	OK	Limited	Si + GaN + InP (heterogeneous)
DARPA Investment			~$100M	~$600M	~$200M	~$300M	~$180M
Programs			Portions of GRATE, ADRT, LPE, and TEAM	MIMIC	SWIFT, TFAST, THz Electronics, SMART	GaN Title III, WBGS-RF, NEXT, MPC, NJTT	COSMOS, DAHI

Materials and device parameters favor a diversity of semiconductors

1. InGaAs channel
2. SiC substrate

Materials & device technology yields new capability

1990 | 2000 | 2010 | Today | 2020 | 2030

TRL 1 — *TRL 7*

MIMIC Program

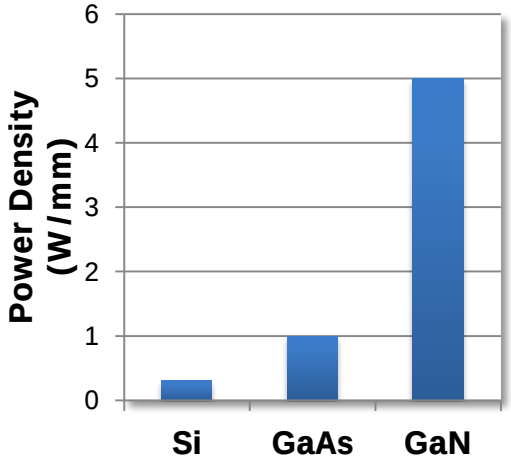
GaAs

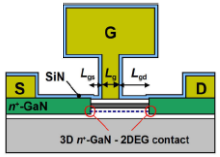
TRL 1 — *TRL 7*

WBGS-RF Program

Early Transistor Research

GaN



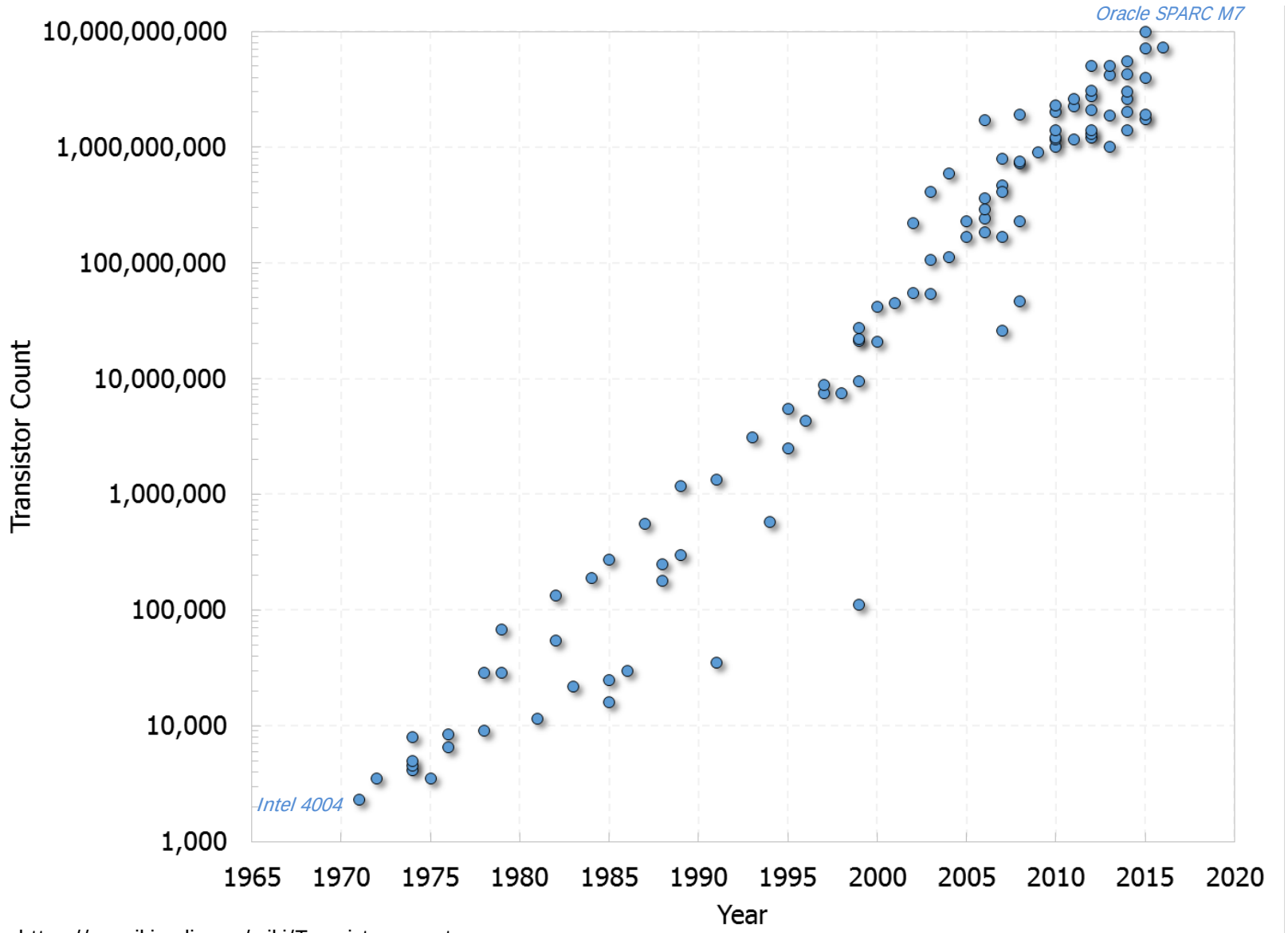


GaN+

DARPA NeXT Program	Higher Frequency; Higher Efficiency
DARPA MPC Program	Higher Efficiency; Advanced Waveforms
DARPA ICECOOL Program	Better Cooling; Higher Output Power

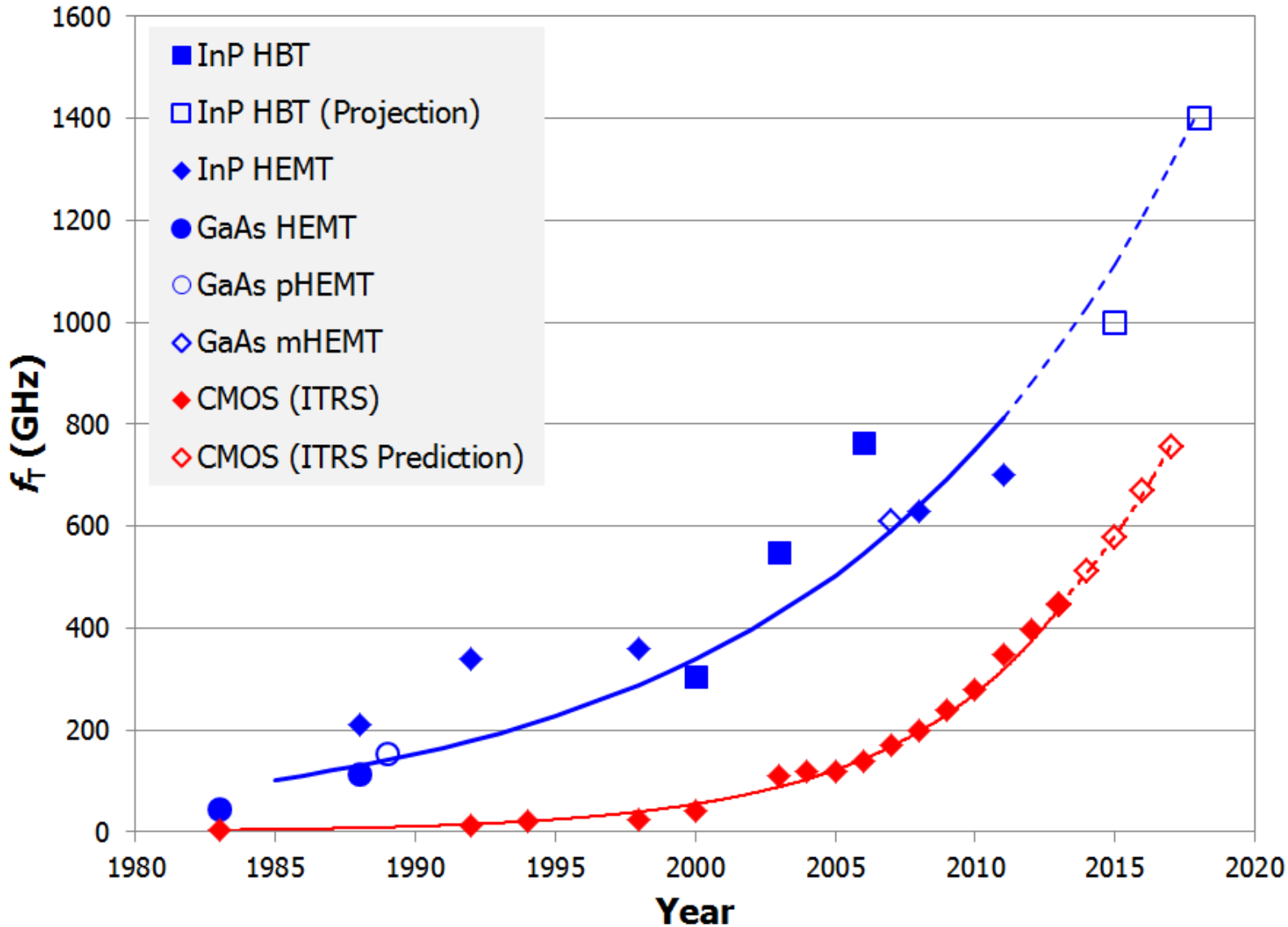
Future Systems

Silicon keeps moving



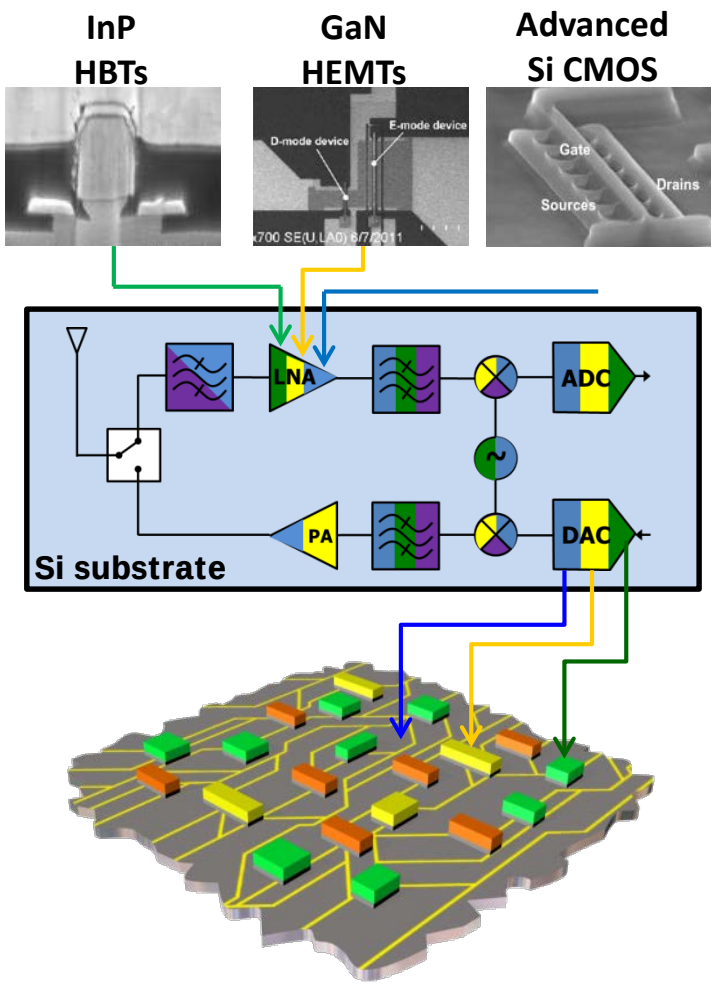
Data source: https://en.wikipedia.org/wiki/Transistor_count

...and getting more capable



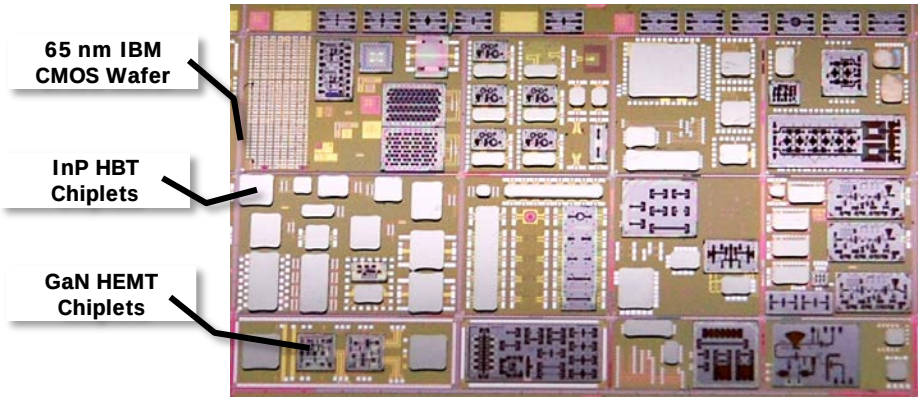
Bringing the two worlds together

Diverse Accessible Heterogeneous Integration (DAHI)



Heterogeneous Integration of a diverse array of devices on a common Si CMOS platform

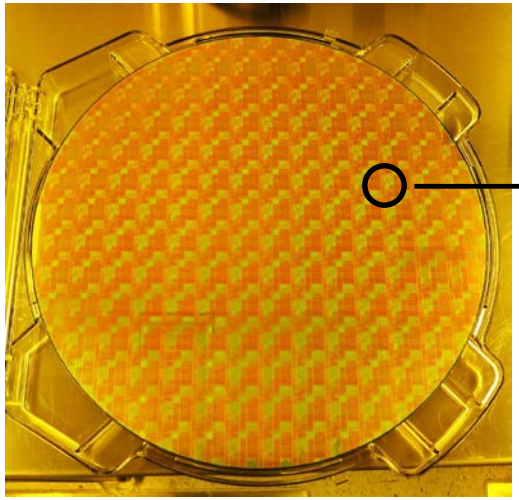
Demonstrated three-technology integration in accessible foundry



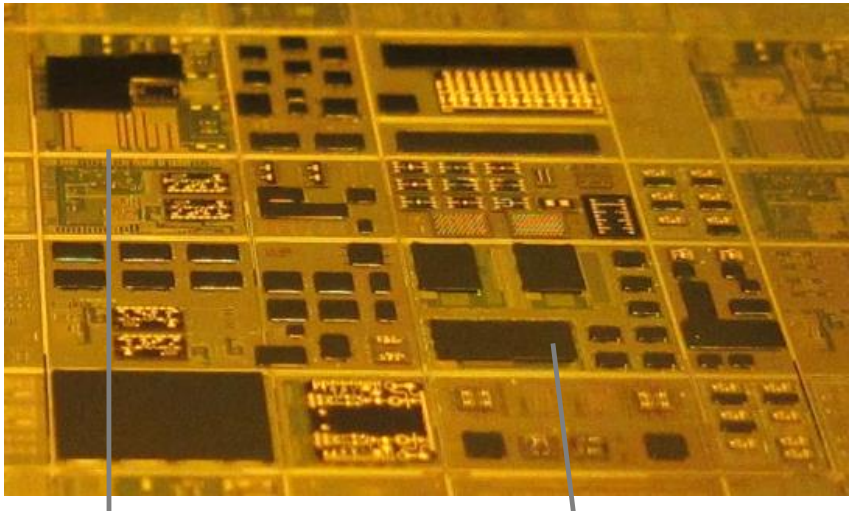
(first three-technology integration demonstrated in Jan 2015)

Goal: To design and build a diverse array of DAHI circuit applications to establish a platform that enables pervasive impact on DoD systems via heterogeneous integration.

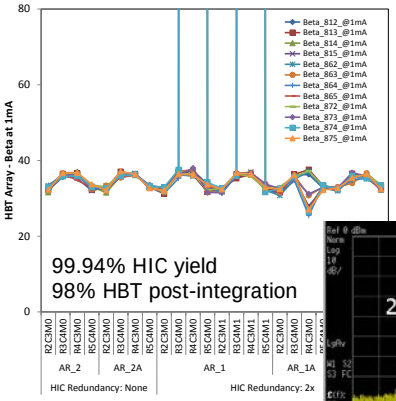
DAHI MPW1: Excellent Yield, Successful Initial Tests



300mm diameter Si CMOS wafer (45nm node)

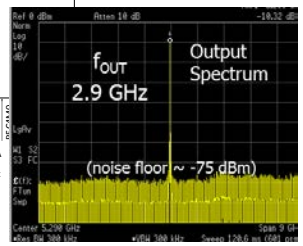


DAHI integration (Dec 2015): Si (45nm), InP (TF5 HBT), GaN (GaN20 HEMT)

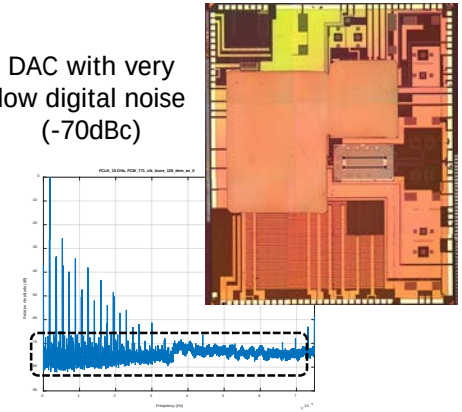


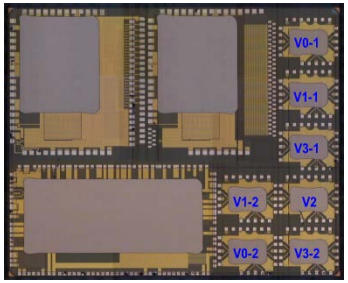
99.94% HIC yield
98% HBT post-integration

High foundry integration yields; test vehicles fully functional



DAC with very low digital noise (-70dBc)

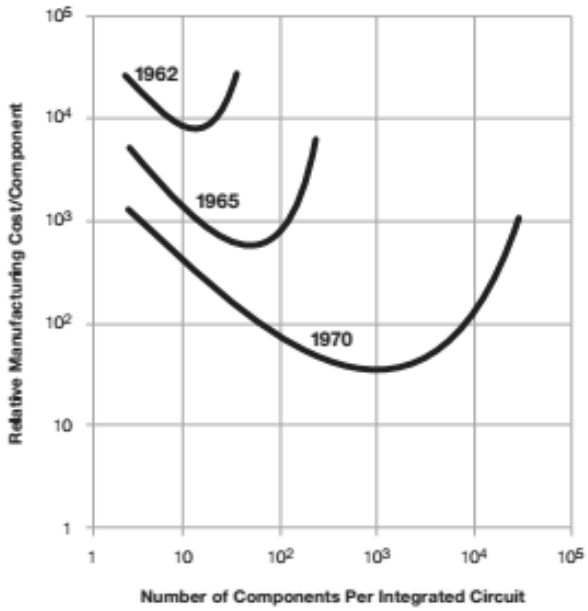


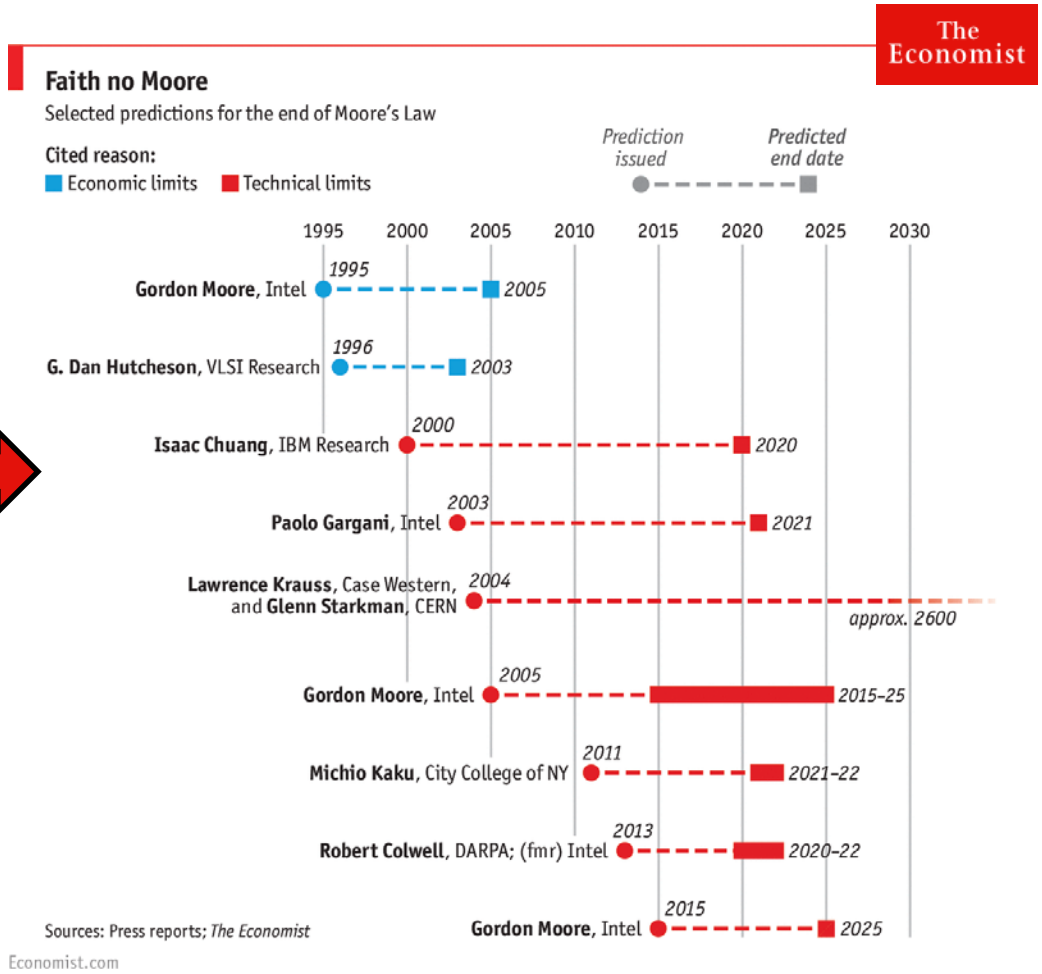


Successful testing identified optimal S/H circuit for ADC (>65dB SFDR @ 2GHz)

End of Moore's Law?

Moore's Law

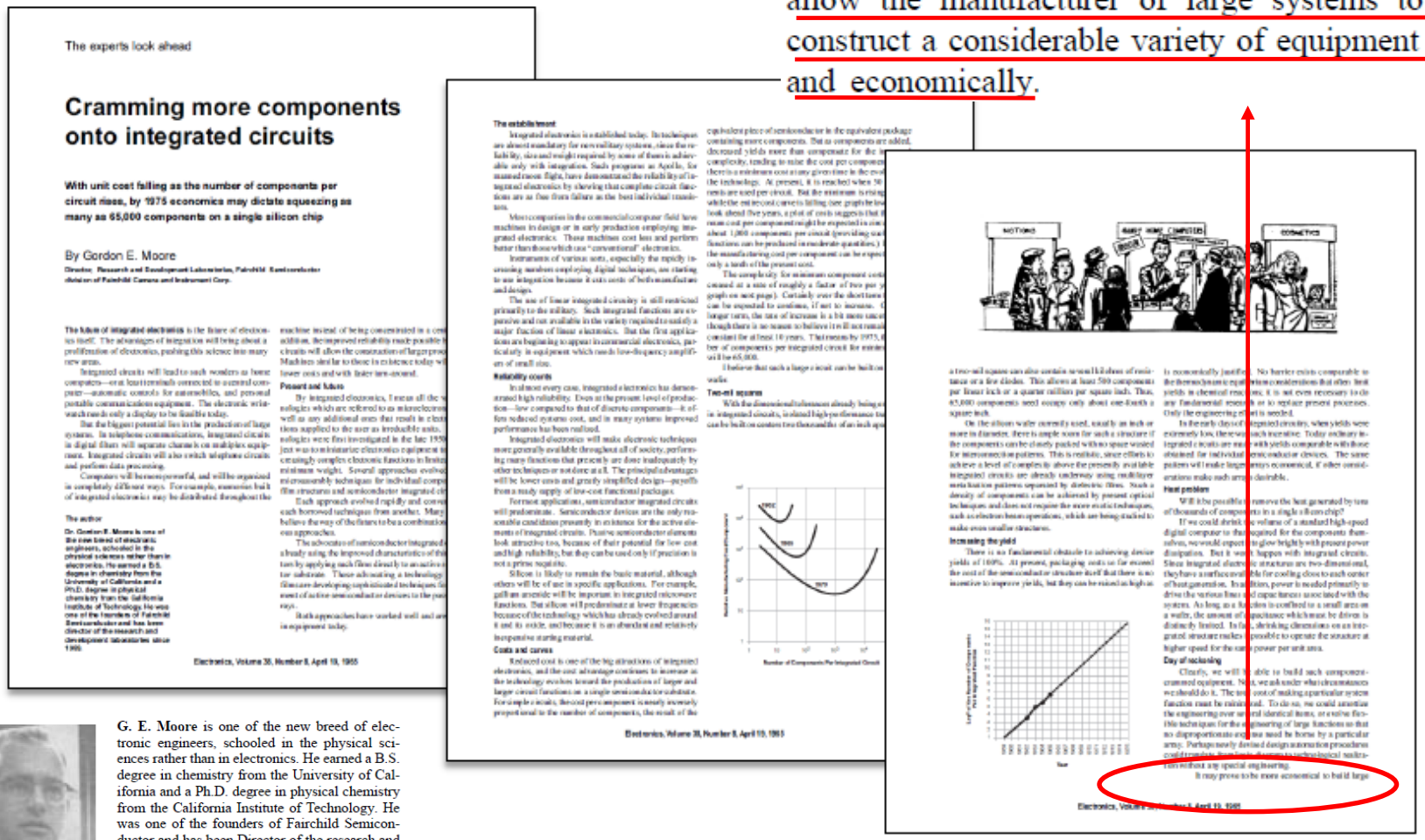




Data source: Electronics Magazine, Economist.com

Moore's Law INCLUDES Heterogeneous Integration

It may prove to be more economical to build large systems out of smaller functions, which are separately packaged and interconnected. The availability of large functions, combined with functional design and construction, should allow the manufacturer of large systems to design and construct a considerable variety of equipment both rapidly and economically.



The experts look ahead

Cramming more components onto integrated circuits

With unit cost falling as the number of components per circuit rises, by 1975 economics may dictate squeezing as many as 65,000 components on a single silicon chip

By Gordon E. Moore

Director, Research and Development Laboratories, Fairchild Semiconductor division of Fairchild Camera and Instrument Corp.

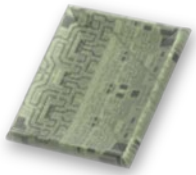
Electronics, Volume 38, Number 8, April 19, 1965

G. E. Moore is one of the new breed of electronic engineers, schooled in the physical sciences rather than in electronics. He earned a B.S. degree in chemistry from the University of California and a Ph.D. degree in physical chemistry from the California Institute of Technology. He was one of the founders of Fairchild Semiconductor and has been Director of the research and development laboratories since 1959.

Integration: Enabling IP and Chiplet Re-use

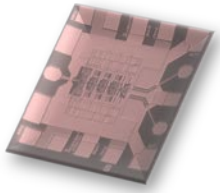
Chiplet process modules designed with IP re-use in mind

GaN

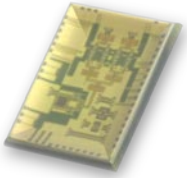


VLSI Si

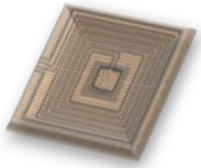
InP



SiGe



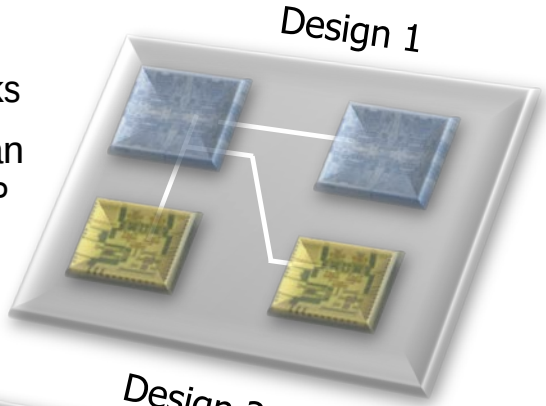
Passives

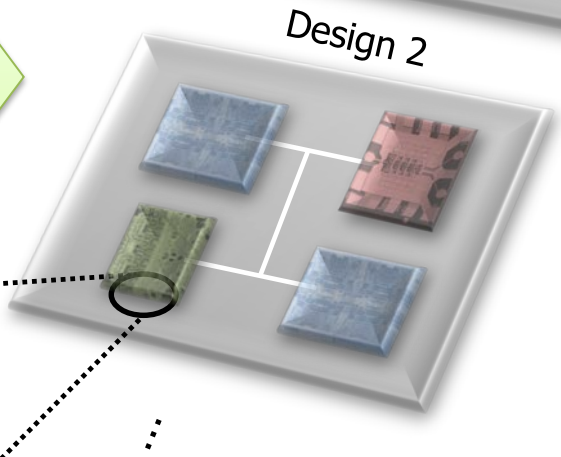


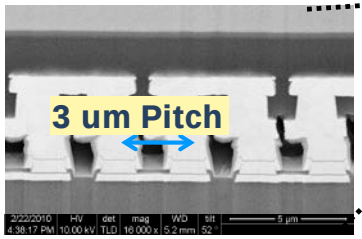
GaAs, MEMS, etc.

- Develop a pre-defined "common" interposer (SiC/Si/Glass) platform
- Populate common platform with library of chiplets of IP/circuit blocks
- Different complex configurations can be formed rapidly with reuseable IP blocks/chiplets

Minimized NRE for rapid system prototyping





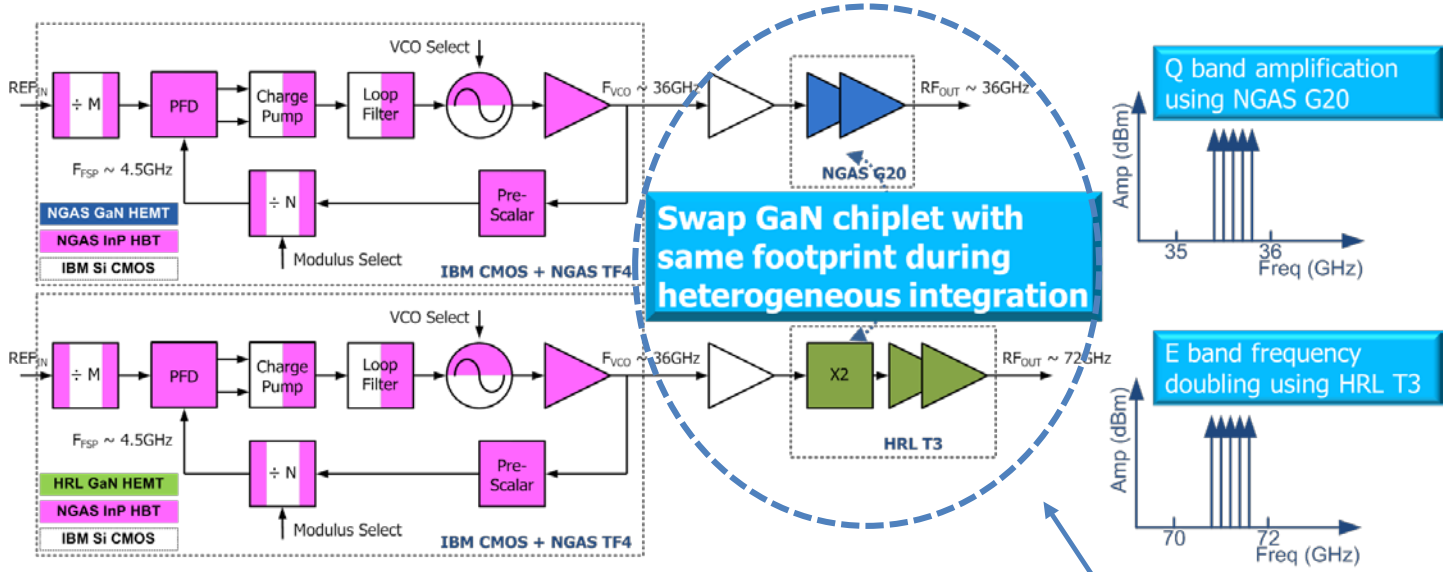


Example interconnect

DAHI-enabled integration technology plus IP re-use ecosystem to speed the design cycle and reduce the access cost

DAHI MPW1:
Dual-Band Frequency Synthesizer Demonstrates Modularity

MPW1 Q/E Dual Band Frequency Synthesizer (36 and 72 GHz)



			Technology			
	Function	Freq (GHz)	CMOS 12SOI	InP TF4	GaN G20	GaN T3
A	Amplifier	36			✓	
	Frequency Doubler	72				✓
B	Buffer	36	✓			
C	Buffer + Amp	36	✓		✓	
	Buffer + FD	72				✓
D	VCO + Buffer + Amp	36	✓	✓	✓	
	VCO + Buffer + FD	72	✓	✓		✓
E	Frequency Synthesizer	36	✓	✓	✓	
	Frequency Synthesizer	72	✓	✓		✓

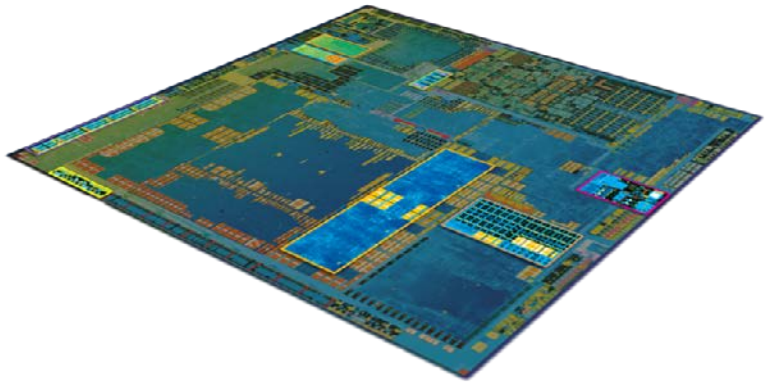
Integration of diverse device technologies enables modular functionality.

What is CHIPS?

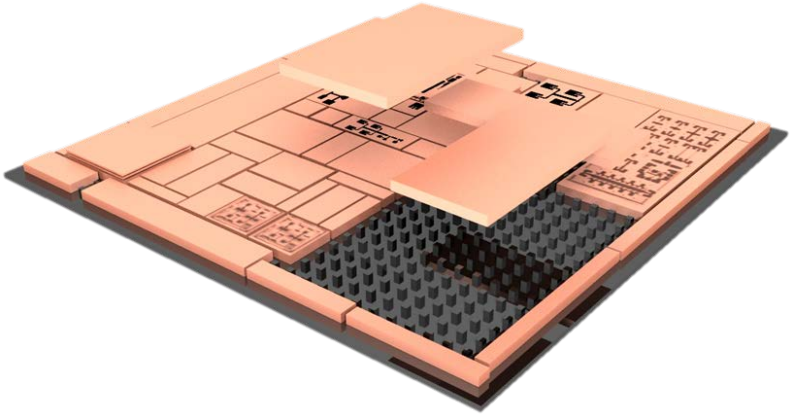
Common Heterogeneous integration and IP reuse Strategies program

CHIPS will develop the **design tools and integration standards** required to demonstrate **modular electronic systems** that can leverage **the best of DoD and commercial** designs and technology.

Today – Monolithic

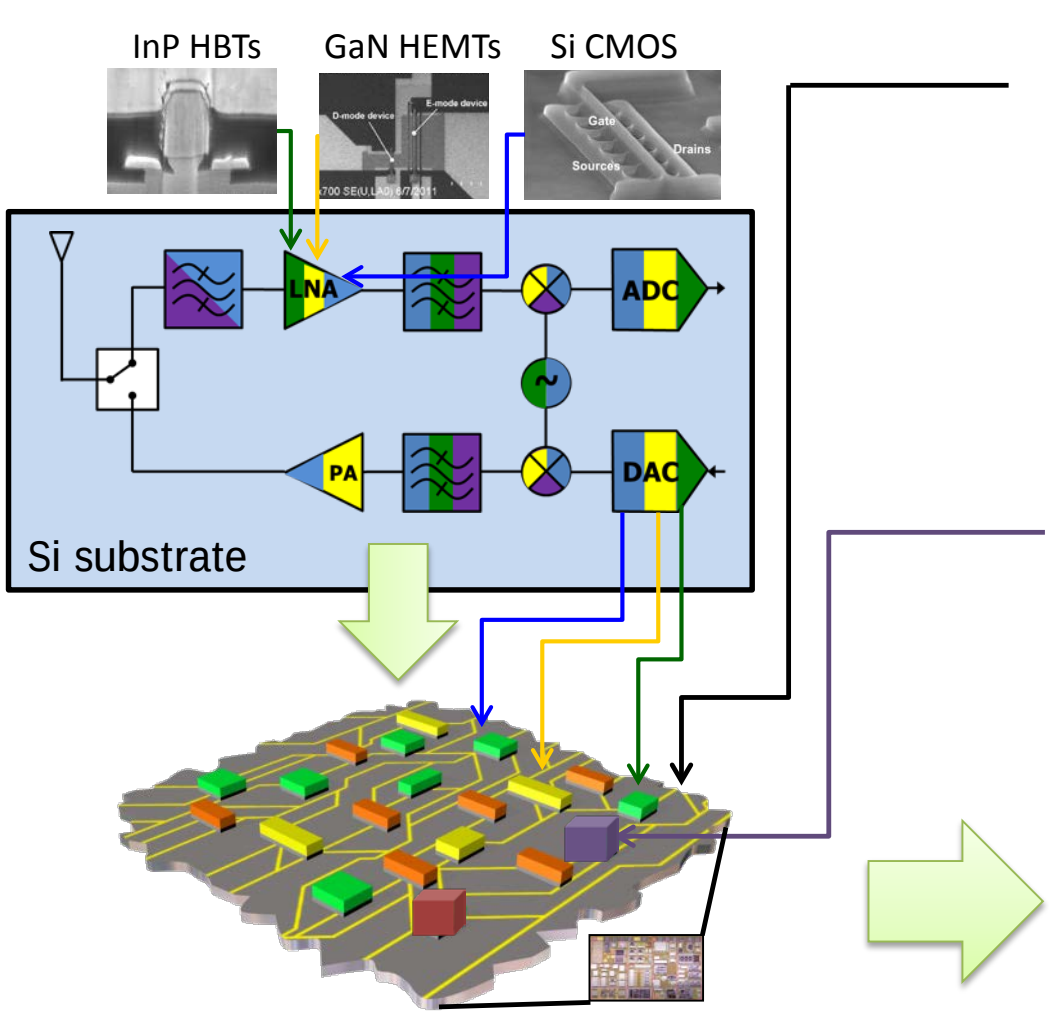


Tomorrow – Modular



CHIPS Proposers Day tomorrow!

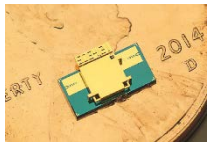
Looking Ahead: Enabling **Rapid** Heterogeneous Technology Uptake



Design Advances

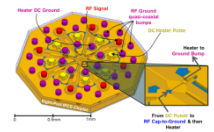
- Advancing CMOS nodes
- Integration-enabled design techniques

Emerging Technologies

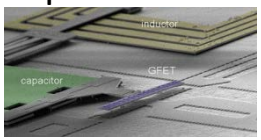


Polystrata High-Q passives

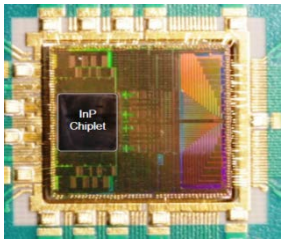
PCM switches



Graphene mixers

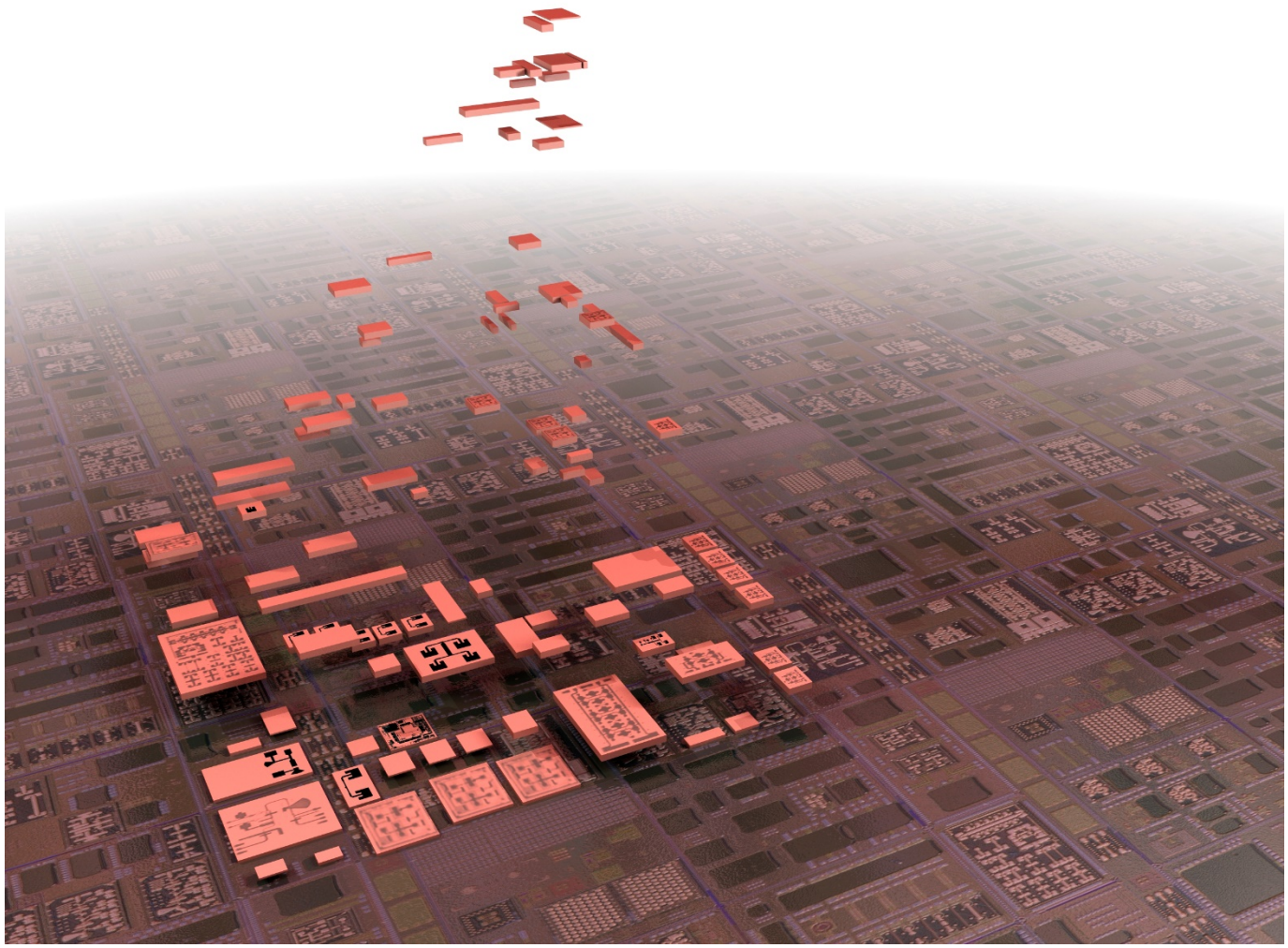


Revolutionary RF/mixed signal systems



Platform gives ability to rapidly add technologies as they are developed

Future of heterogeneous integration...



A far, far better place to be.

www.darpa.mil

Putting The ‘System’ Back In Microsystem

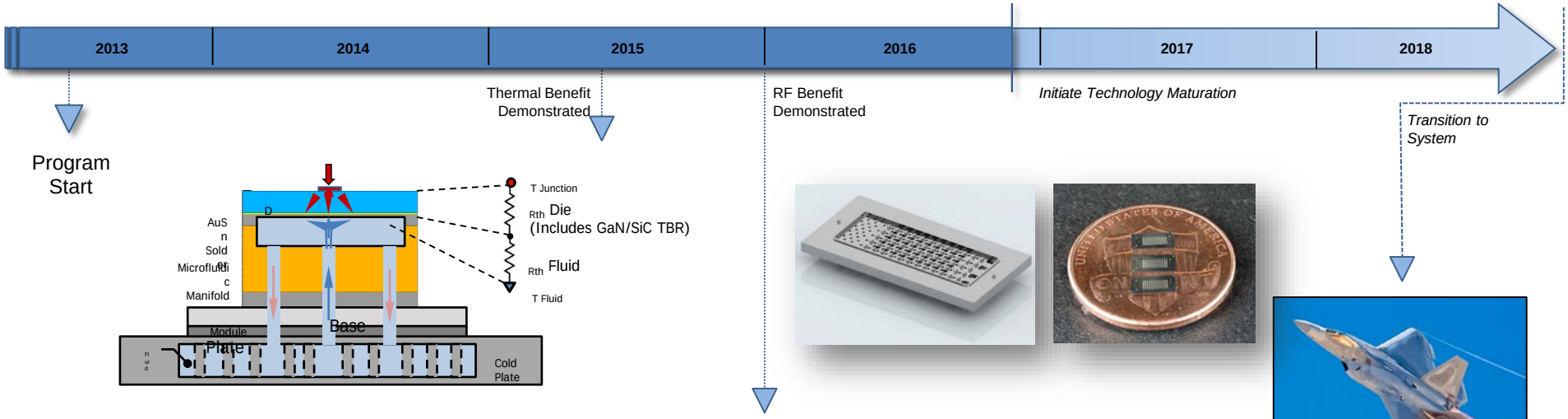
Dr. Kenneth Plaks
Program Manager
Microsystems Technology Office

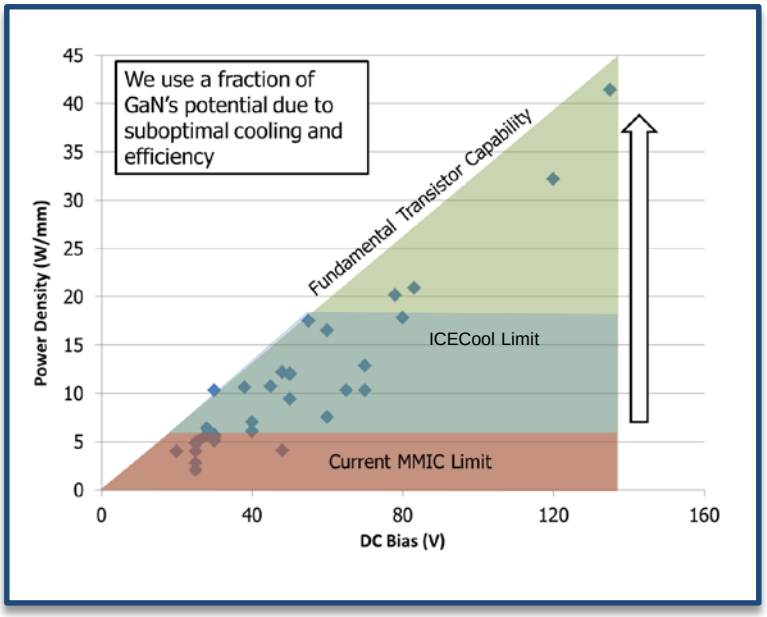
Proposers Day

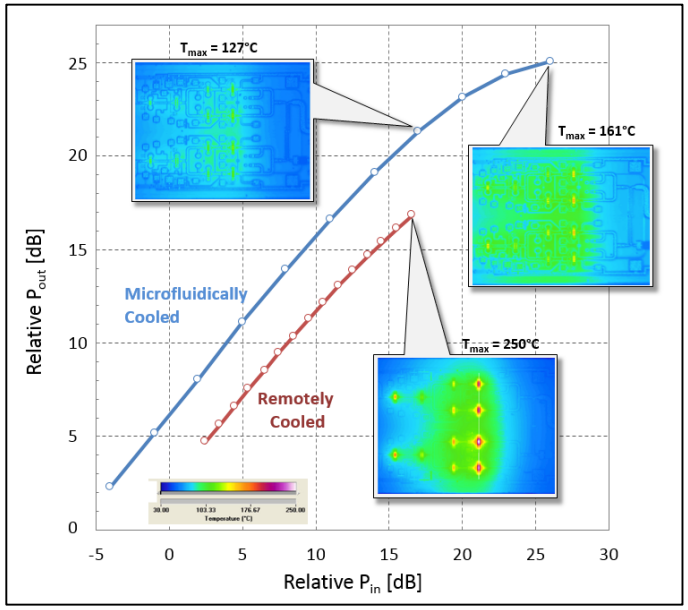
September 20, 2016

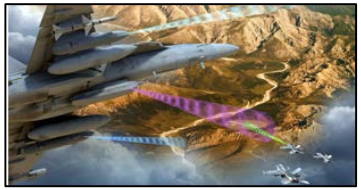
Distribution A: Approved for public release

ICECool: Thermal Management of GaN PAs



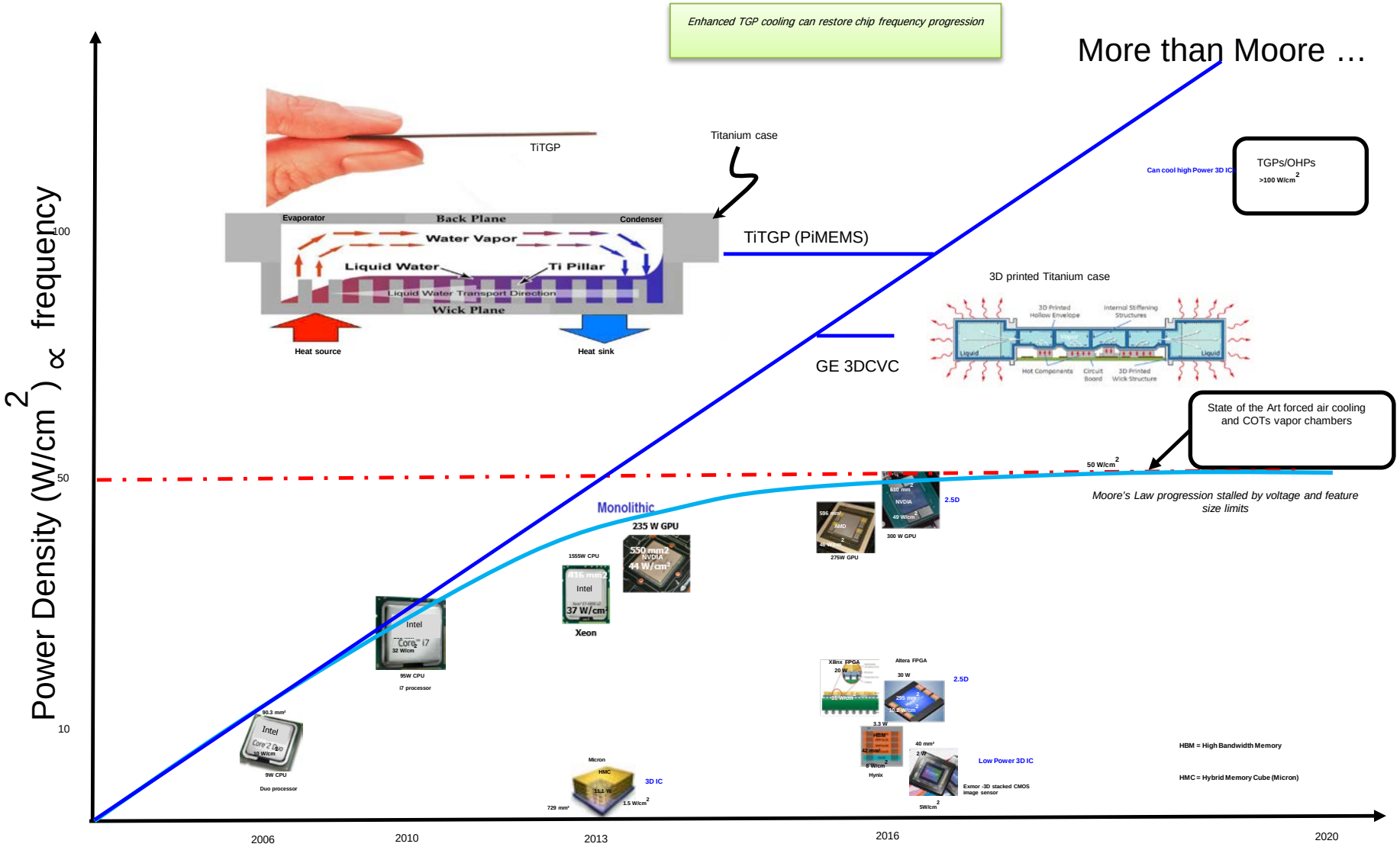




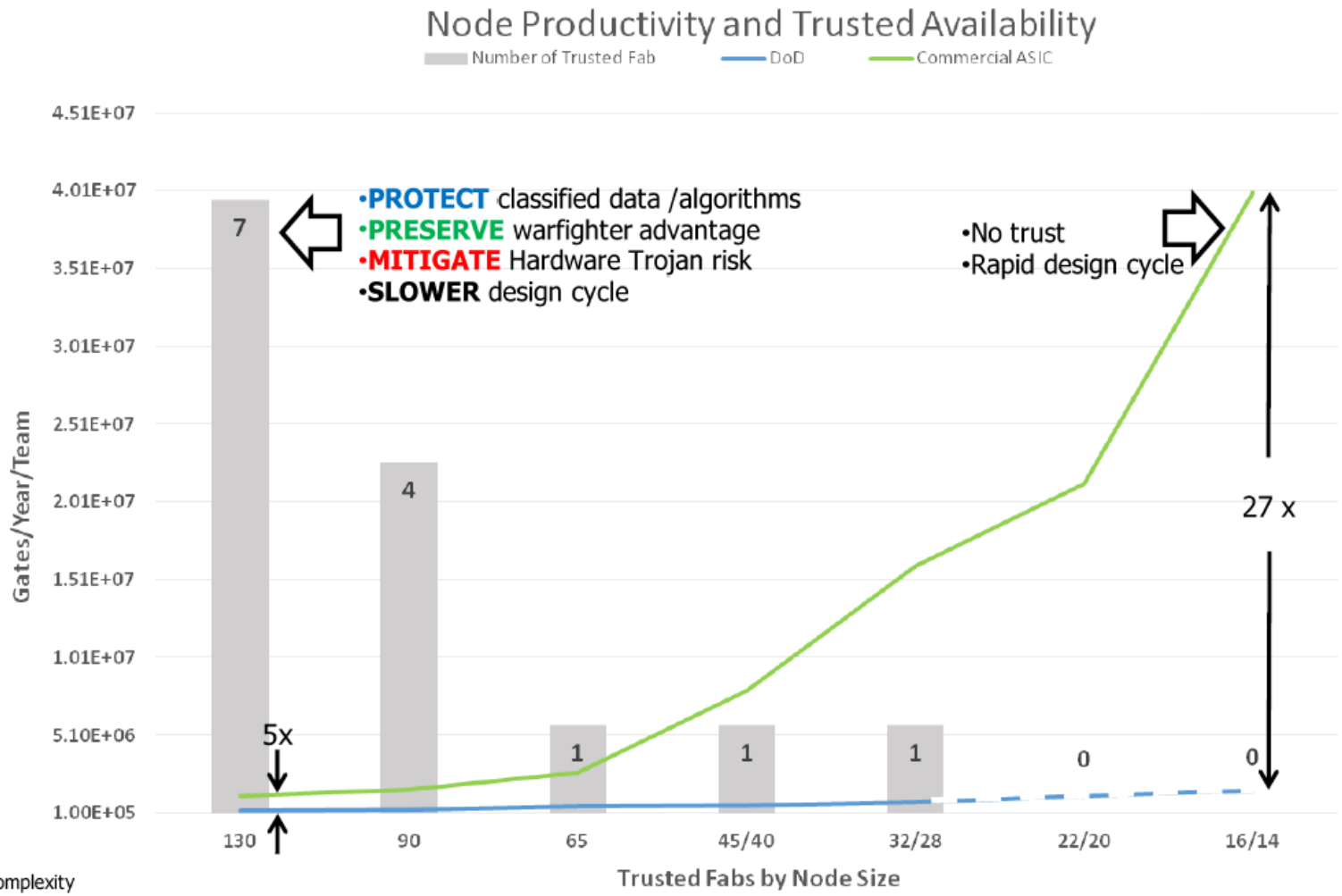


Images of results courtesy of John Ditri, Lockheed Martin

DARPA TGP transition into DoD systems



The ASIC Dilemma

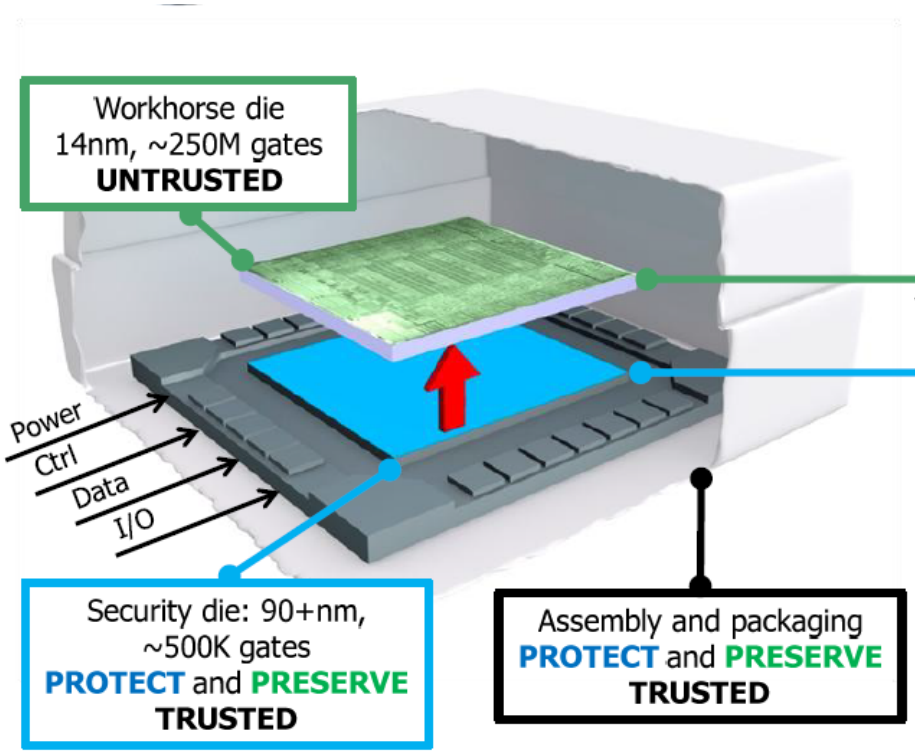


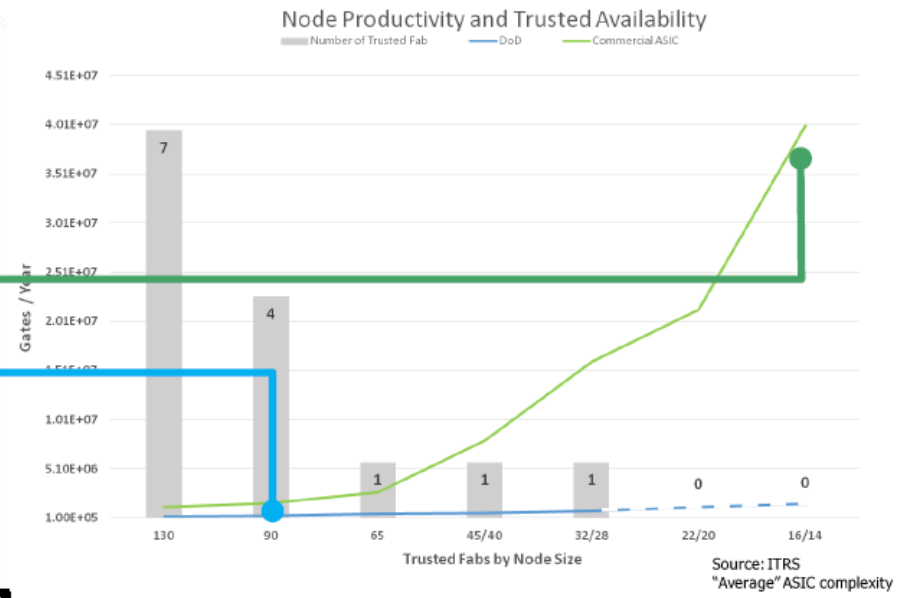
Source: ITRS
"Average" ASIC complexity

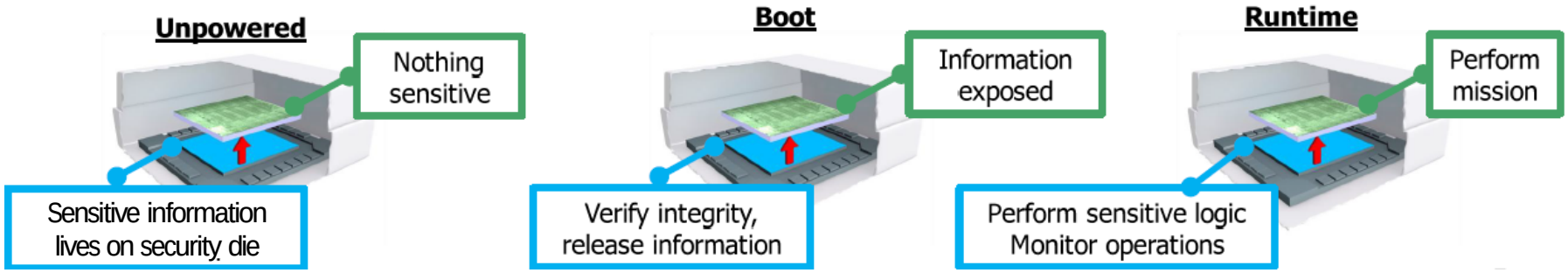
How do we ensure that the warfighter has access to state of the art electronics?

Distribution Statement "A" (Approved for Public Release, Distribution Unlimited)

ASIC Trust Solution



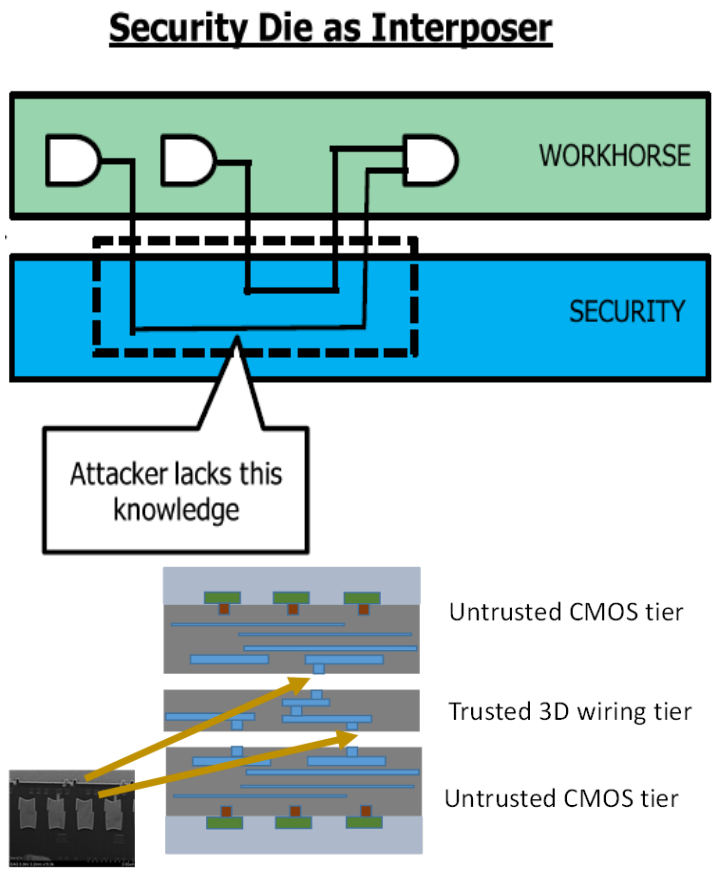




Malicious Logic: Passive Techniques

Goal: make it harder to insert hardware Trojan/malicious logic

Mitigate risk through obfuscation

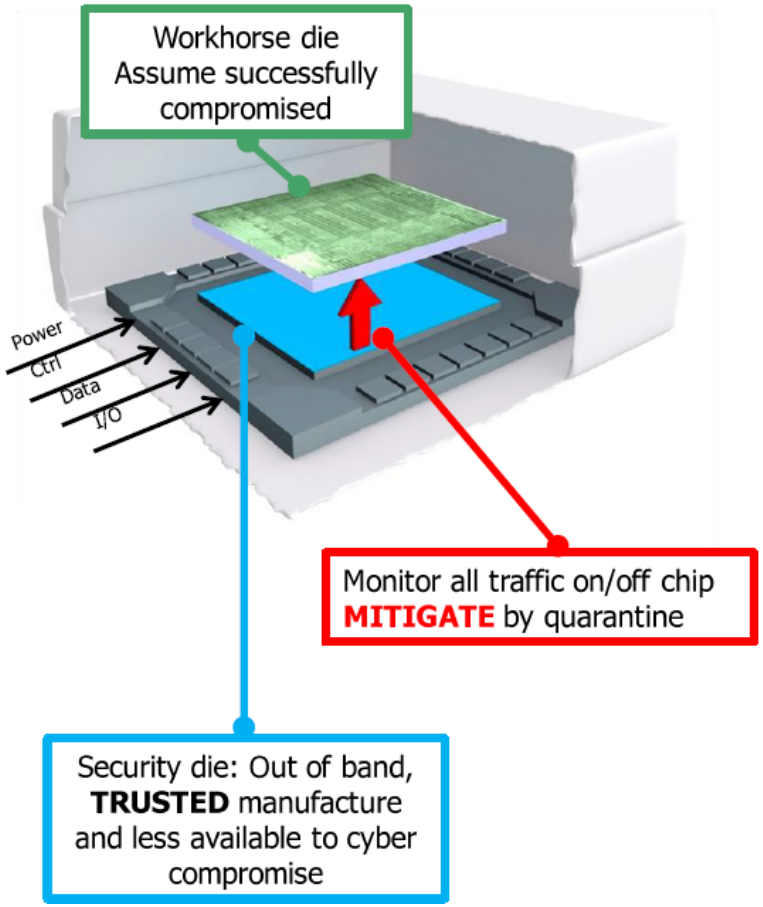


Key Research Questions:

- What are the metrics & how do we measure effectiveness of obfuscation techniques?
- What design tools are needed to facilitate implementation of obfuscation?
- Is the solution scalable? What is the solution's impact on performance?

Malicious Logic: Active Techniques

- Assume: attacker has successfully compromised untrusted portion
- Goal: Mitigate impact and contain contamination
- Security die moderates all signals:
  - Enables active monitoring
  - IO
  - Control
  - State (privilege, etc.)
  - Out of band with mission circuits
  - Prevent spread of contagion by quarantine



Key Research Questions:

- How do we detect it?
- How do we mitigate its impact?
- Is the solution scalable? What is the solution's impact on performance?

www.darpa.mil

Revolutionary Advances in System-on-a-Chip (SoC) Architecture, Design, and Fabrication

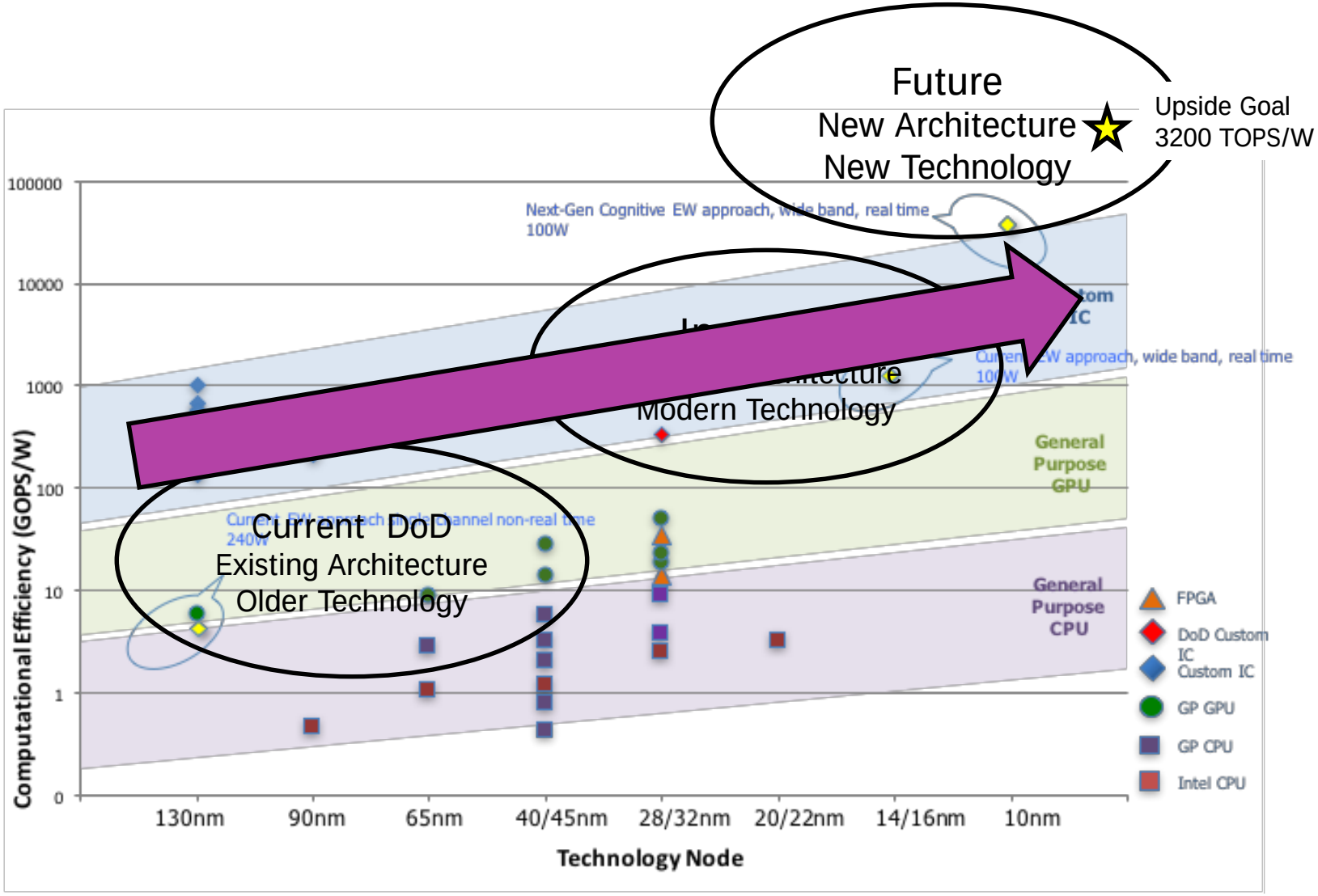
Dr. Linton Salmon
Program Manager
Microsystems Technology Office

Proposers Day

September 20, 2016

Distribution A: Approved for public release

DoD SoC Needs



Salmon Areas of Interest

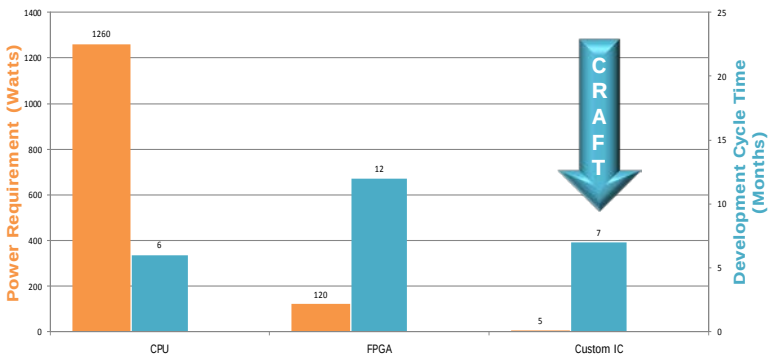
- ***Provide the best possible microelectronic SoCs for DoD systems through improvements in architecture, design, and fabrication***
- In process – Increase DoD use of custom accelerators in leading-edge CMOS
  - Utilize the best commercial design practices
  - Provide access to commercial FinFET fabrication technology
  - Make design 10X more efficient
- Next up – Secure the hardware (SSITH)
  - Develop best methods to secure the hardware
  - Utilize CRAFT capability to establish architectures to implement those methods
- Future – Move beyond accelerators
  - Revolutionary circuit architectures
    - Massive 3D architectures vs 2D architectures
    - Processing in memory
  - Revolutionary fabrication
    - Monolithically stacked devices
    - Novel hardware driven by cortical architectures
- Joint University Microelectronics Program (JUMP) – Do pathfinding at scale together with industry and academia
  - DARPA program funding approved – waiting for industrial commitment

Approved for public release: distribution unlimited

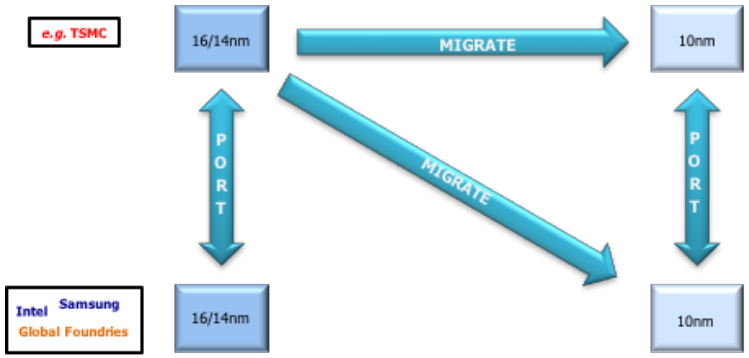
CRAFT – Circuit Realization at Faster Timescales

- Vision

  "To sharply reduce the barriers to DoD use of custom-integrated circuits built using leading-edge CMOS technology while maintaining the high level of performance at power promised by this technology."



Reduce Design Effort



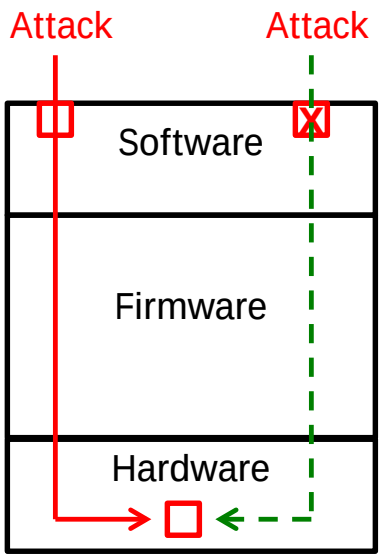
Enable Porting of Designs

- Summary
  - Kickoff – March 29, 2016
  - End of Phase I – July, 2017
  - 6 teams consisting of 20 performers

SSITH: Hardware State Awareness to Protect Electronic Systems
(Program Concept)

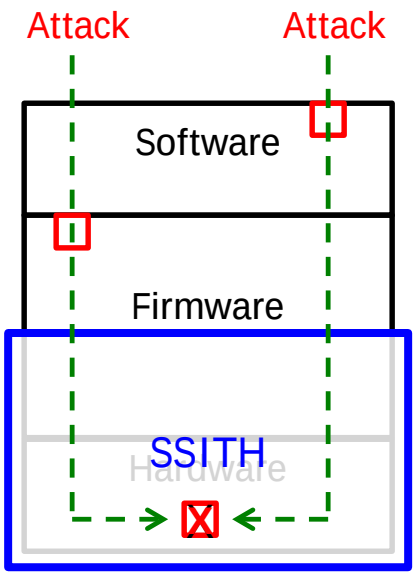
Today: Patch and Pray

*2800 vulnerability instances
2800 software patches



Hardware Vulnerability Class

Future: SSITH



Hardware Vulnerability Class

**7 vulnerability classes
7 hardware solutions

Critical Characteristics

- Secure
- Low PAP impact
- Scalable
- Flexible
- Adaptable

SSITH will address hardware vulnerabilities at their source and address current and future vulnerabilities

*2015 MITRE-recorded hardware vulnerabilities (CVE)

**2015 MITRE-defined hardware vulnerability classes (CWE)

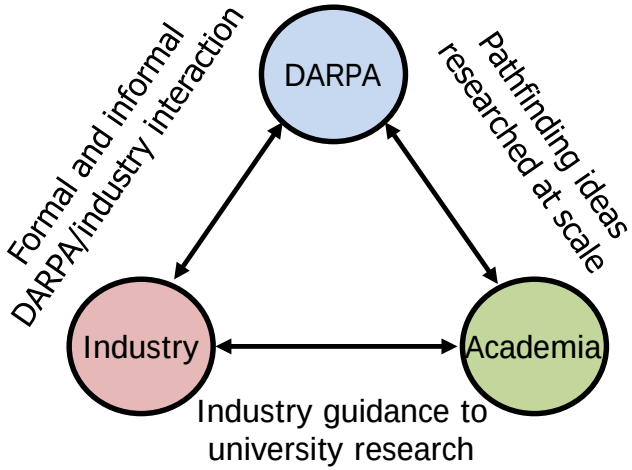
Approved for public release: distribution unlimited

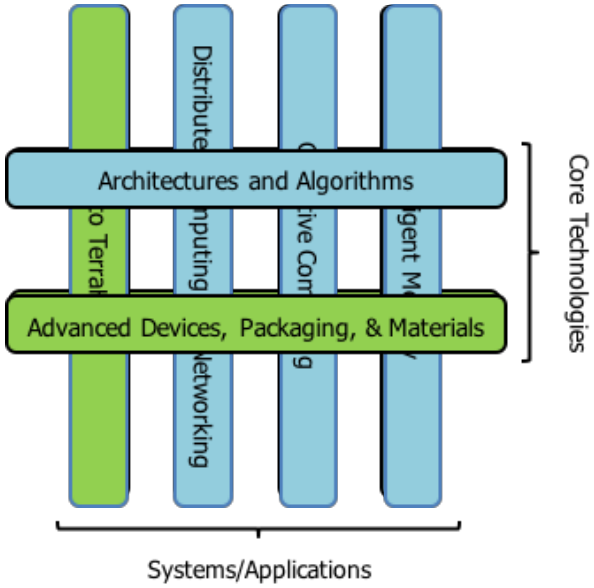
Joint University Microelectronics Program (JUMP)

JUMP Vision

To drive pathfinding research efforts in new computing and communication technologies through enhanced DARPA-industry collaboration, funding, and guidance of university center research

- Objectives
  - Drive long-term research in microelectronics with key players in industry and from academia
  - Develop long-range ideas that drive formation of new DARPA programs
  - Provide a forum for DARPA-industry interactions
- Program overview
  - 6 centers focused on 6 major long-range microelectronic research themes
  - DARPA + industrial sponsors
  - US university faculty as PIs





My Challenge to You

- Joint with me to leverage the advances driven by CRAFT
- Join with me to leverage the DARPA/industry/academia pathfinding opportunities in JUMP
- Join with me to define these new programs
  - Hardware security
  - Revolutionary computing circuit architectures and hardware

www.darpa.mil

The Return of Photonics (Beyond Datacom)

Dr. Josh Conway
Program Manager
Microsystems Technology Office

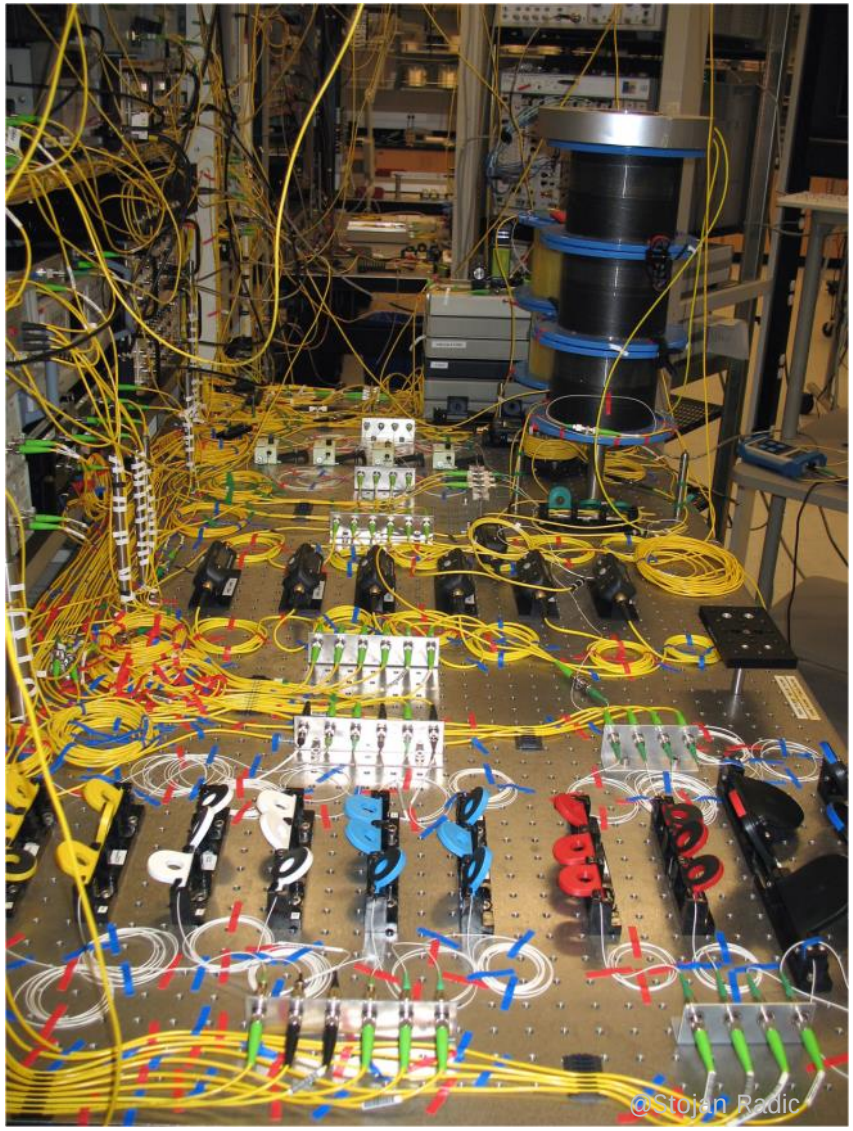
Proposers Day

September 20, 2016

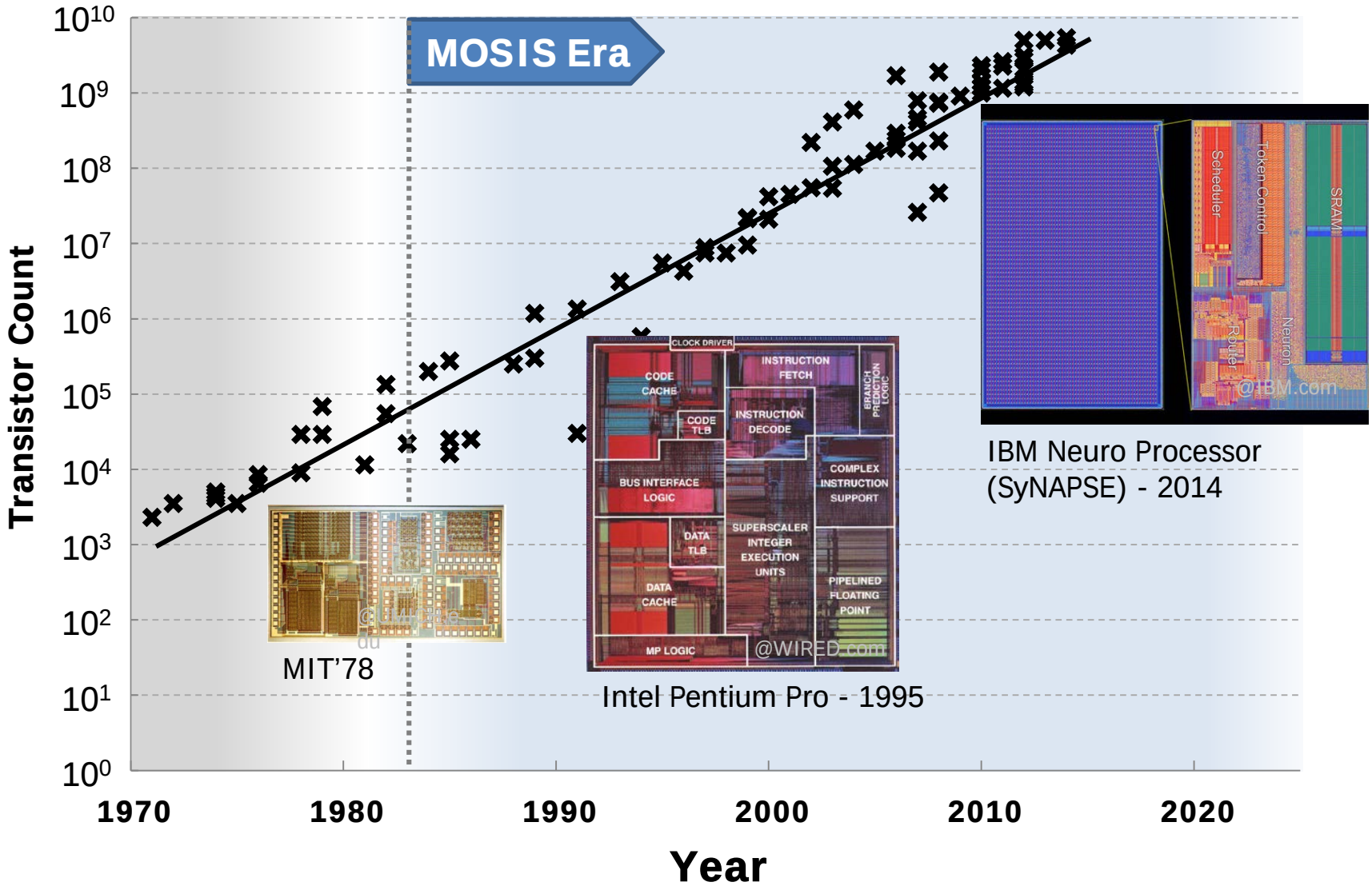
Distribution A: Approved for public release

Cutting Edge Photonics Research

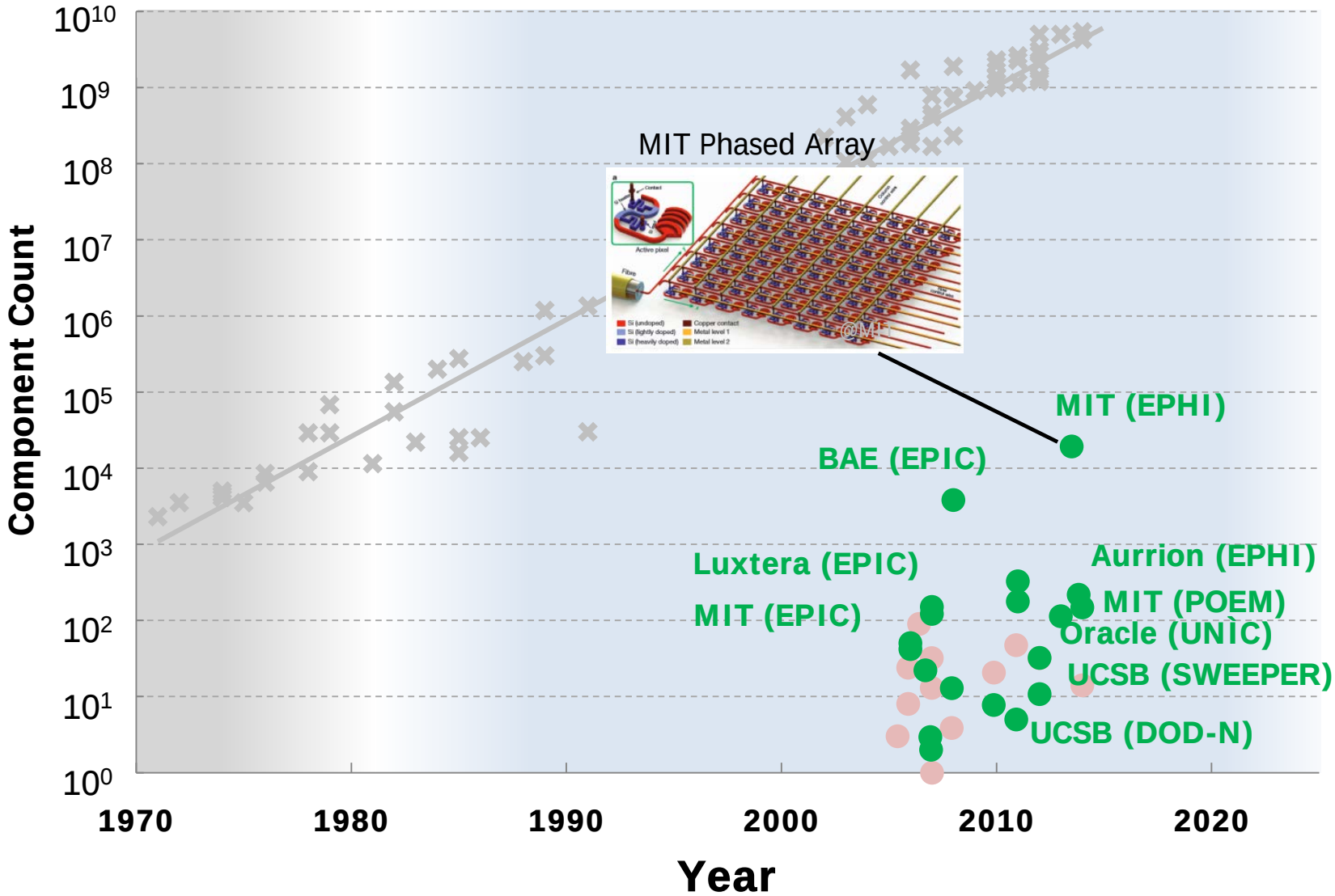
Bell Labs, 2007



Moore's Law

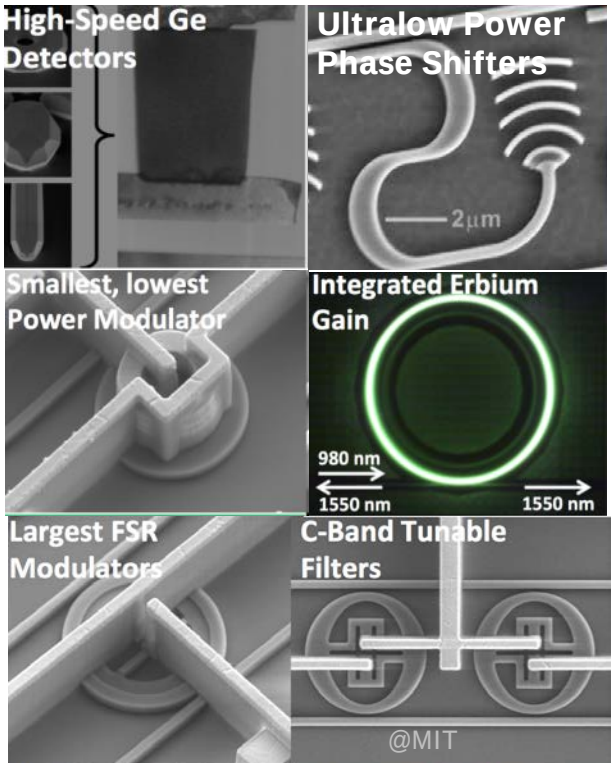

MOSIS Era
Transistor Count
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
1970
1980
1990
2000
2010
2020
Year
MIT'78
Intel Pentium Pro - 1995
CLOCK DRIVER
CODE CACHE
INSTRUCTION FETCH
BRANCH PREDICTION LOGIC
CODE TLB
INSTRUCTION DECODE
BUS INTERFACE LOGIC
COMPLEX INSTRUCTION SUPPORT
DATA TLB
SUPERSCALER INTEGER EXECUTION UNITS
DATA CACHE
PIPELINED FLOATING POINT
MP LOGIC
@WIRED.com
Scheduler
Token Control
SRAM
Neuron
Router
@IBM.com
IBM Neuro Processor
(SyNAPSE) - 2014

Exponential Component Growth

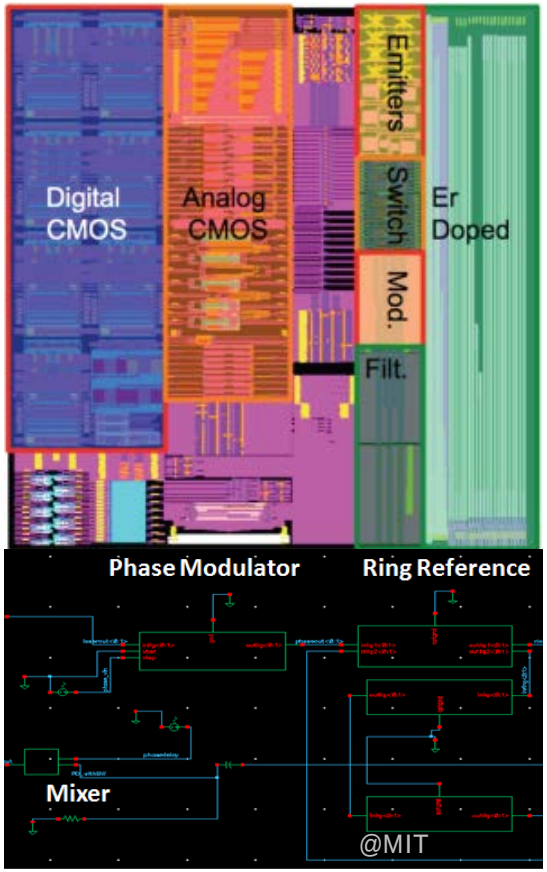


The E-PHI Design and Process Technology

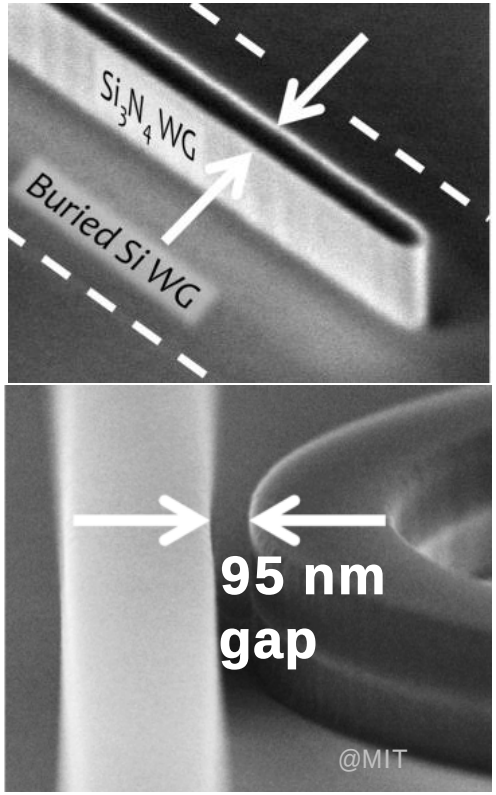
Component Library



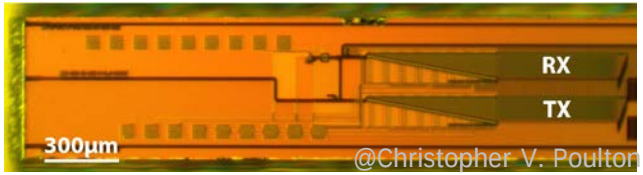
Conventional Semiconductor Design Tools

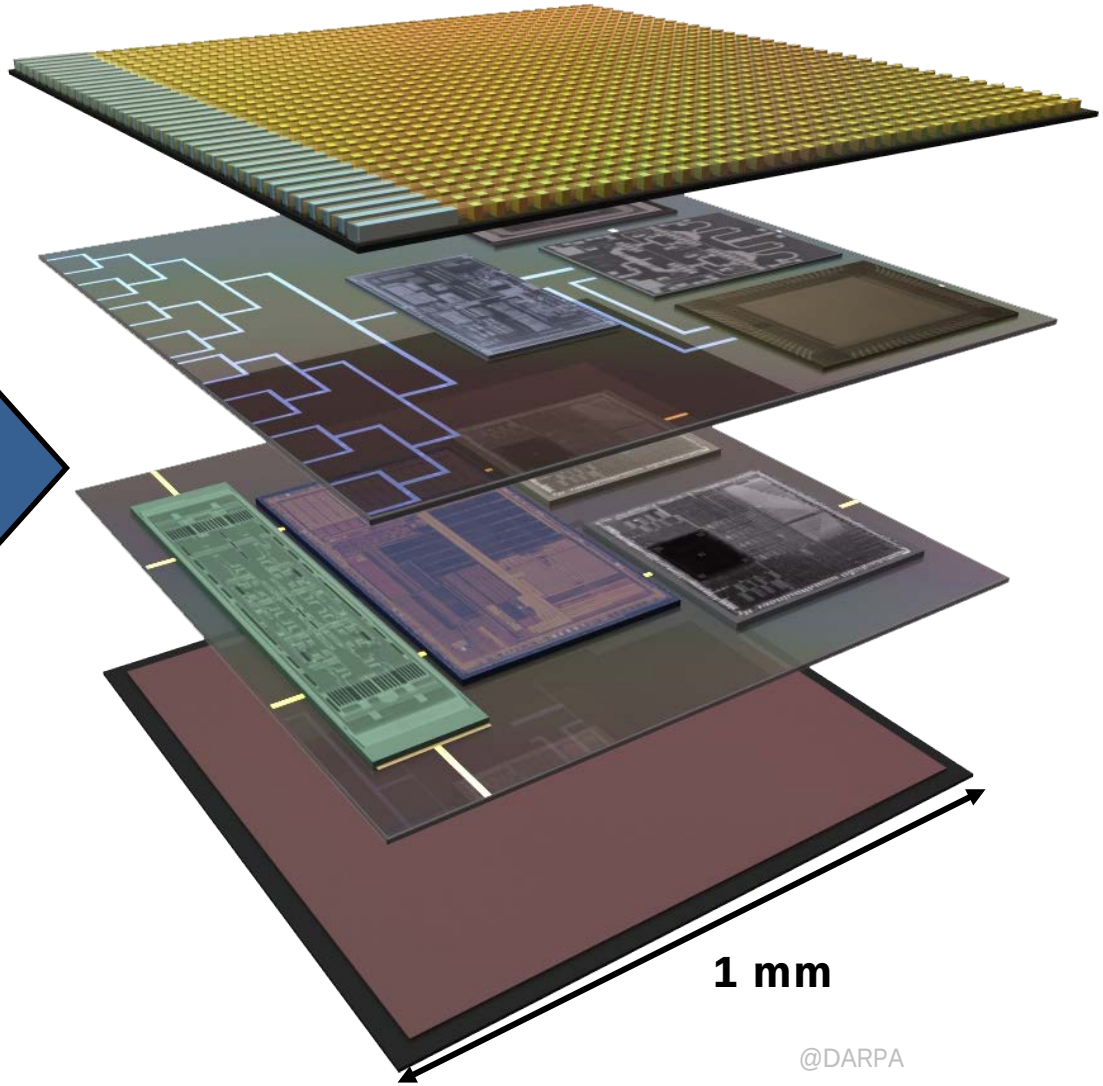


Process Control

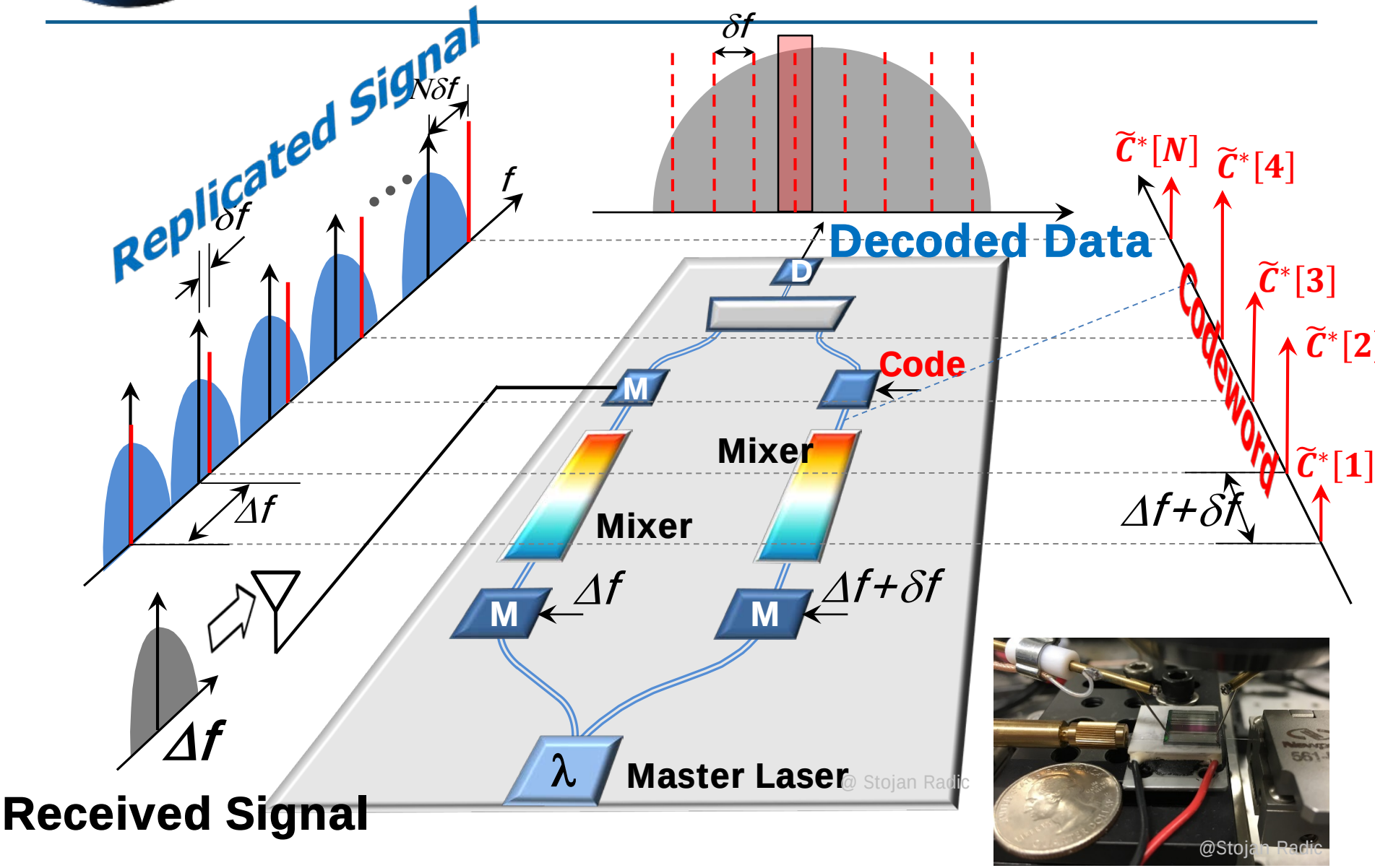


Modular Optical Aperture Building Blocks (MOABB)





Hyper-Wideband Communications



www.darpa.mil

Distribution A: Approved for public release

This Program Manager Will Eventually Vanish

Dr. Troy Olsson
Program Manager
Microsystems Technology Office

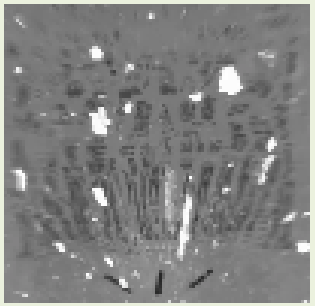
Proposers Day

September 20, 2016

Distribution A: Approved for public release

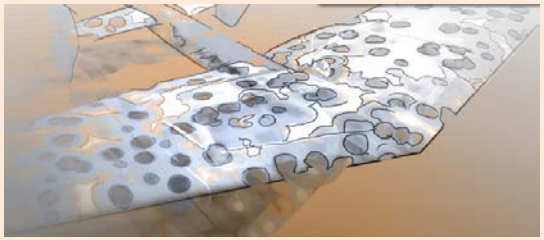
Overview

Vanishing Programmable Resources (VAPR)



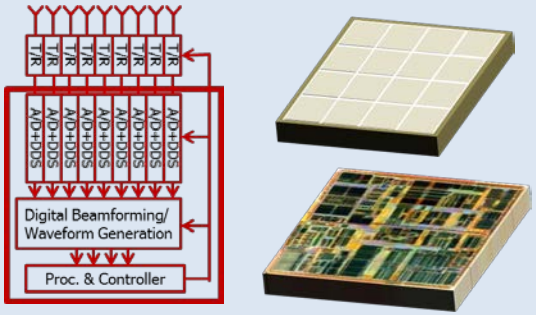
Vanishing microsystems

Inbound, Controlled, Air-Releasable, Unrecoverable Systems (ICARUS)



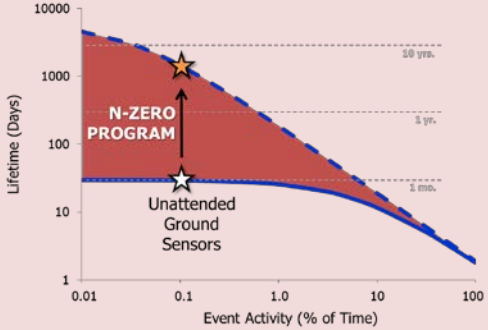
Vanishing air delivery

Arrays at Commercial Timescales (ACT)



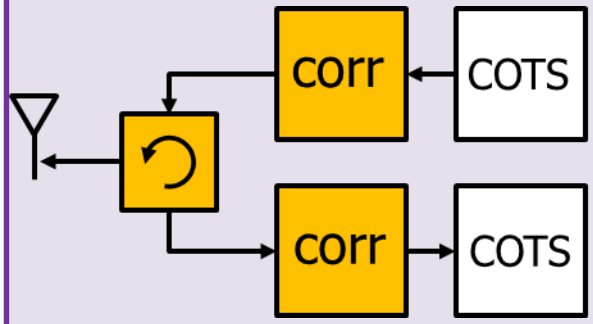
Lower NRE phased arrays using common hardware

Near Zero Power RF and Sensor Operations (N-ZERO)



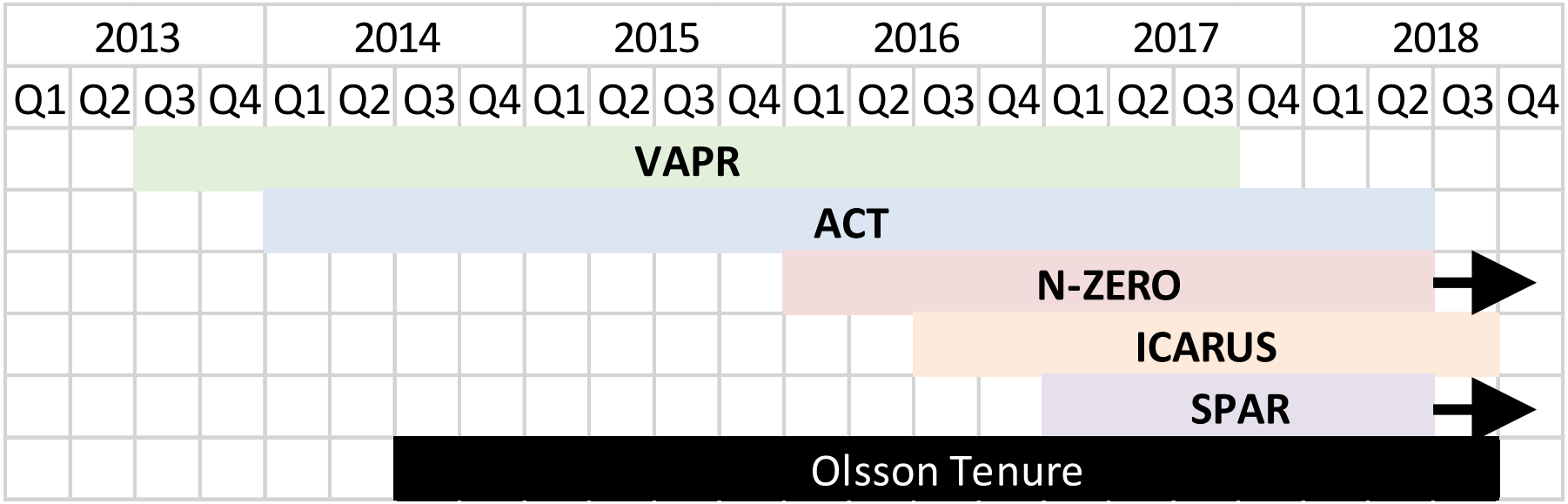
Long lifetime wireless sensors

Signal Processing at RF (SPAR)



Suppress in-band interference

Timeline


2013
2014
2015
2016
2017
2018
Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4
VAPR
ACT
N-ZERO
ICARUS
SPAR
Olsson Tenure

Vanishing Programmable Resources (VAPR)

Program Goals:

- Demonstrate a vanishing wireless sensor node
  - Remnants ~ 100 microns
  - Long life, reliable, stable until trigger
  - Rapidly vanishes upon triggering

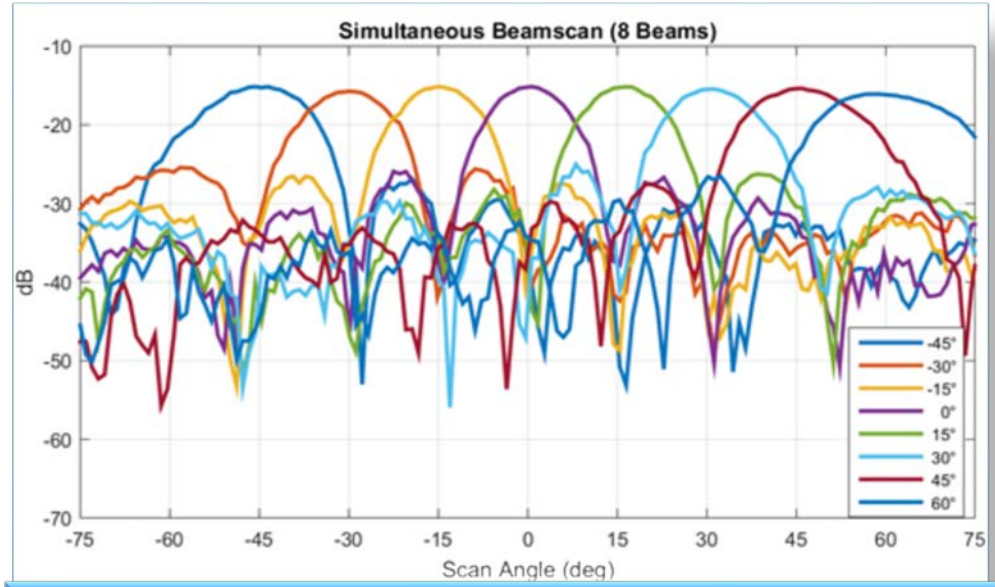
Next Steps:

- MILSPEC testing
- Manufacturing transition
- Operationally relevant demonstration

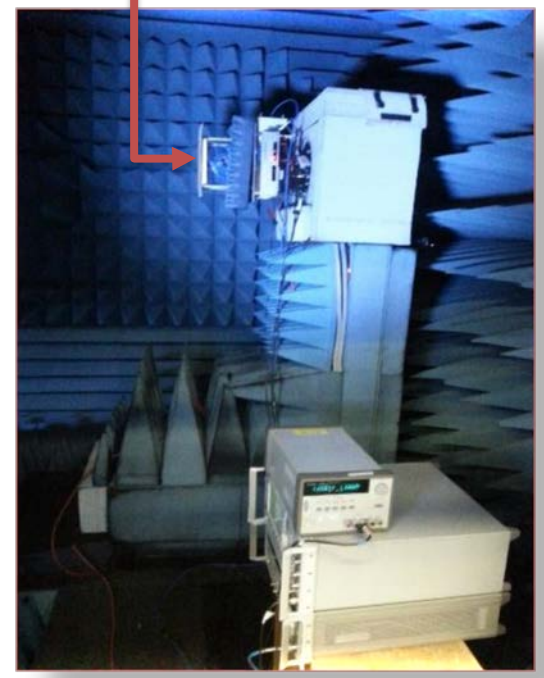
Vanishing Wireless Sensor Demonstrated

Rockwell Collins ACT TA1 Common Module (CM)

The Rockwell Collins ACT CM can produce multiple, independent beams simultaneously (8 shown at 4.4GHz)



8 Simultaneous Measured Beams

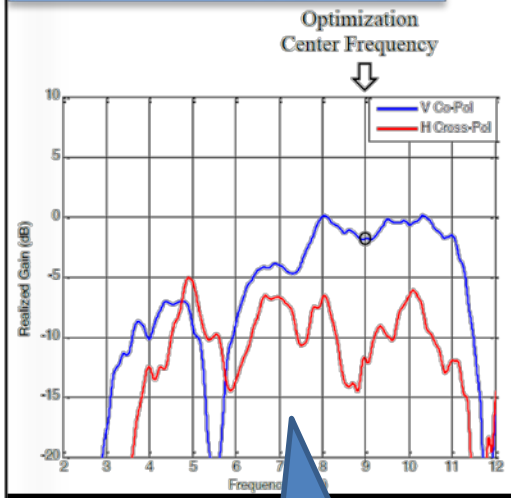


CM on Test Range

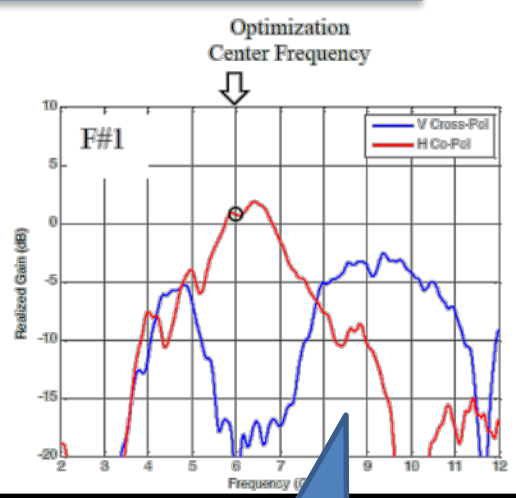
GTRI ACT TA2
Software Defined Modular Array Antenna (SDMAA)

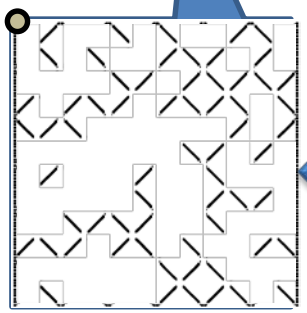
The GTRI Reconfigurable Antenna can Tune for Frequency and Polarization

Tuned 9 GHz, V-Pole

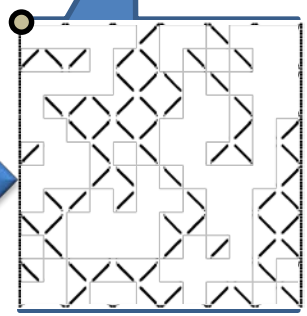


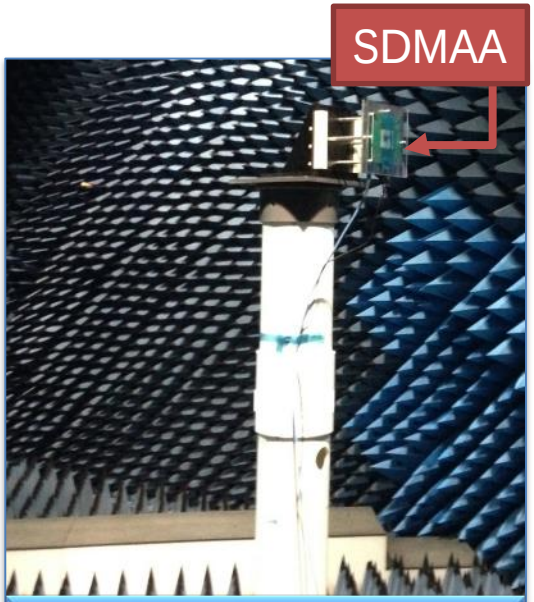
Tuned 6 GHz, H-Pole



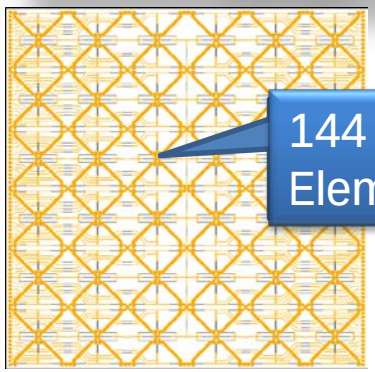


Switch Pattern





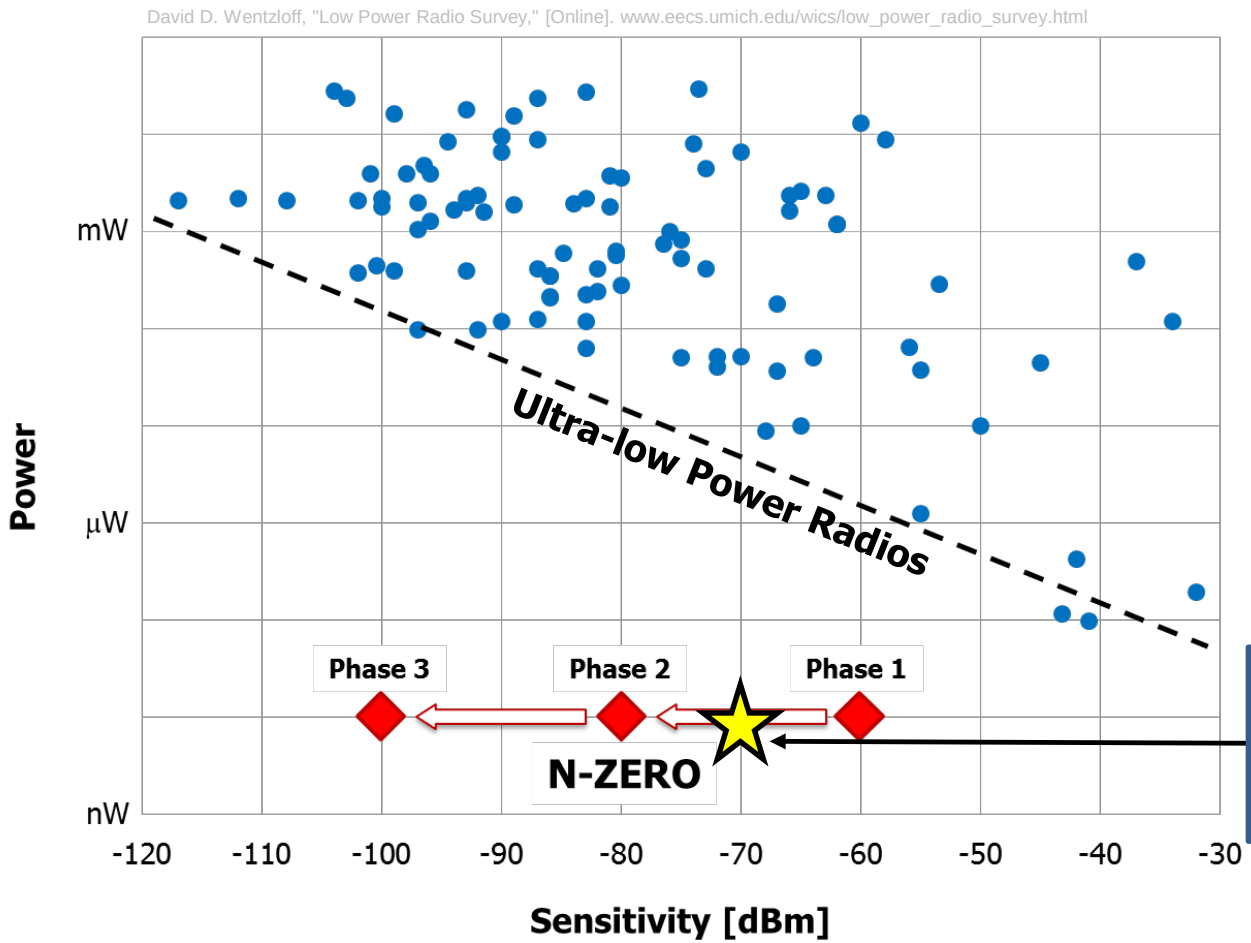
SDMAA on the Test Range



144 Switch Elements

SDMAA Single Element

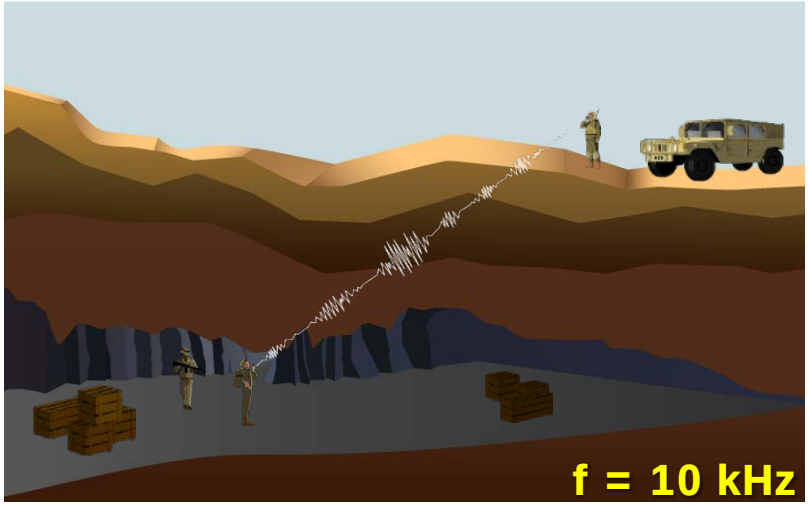
Near Zero Power RF and Sensor Operations (N-ZERO) RF Wakeup



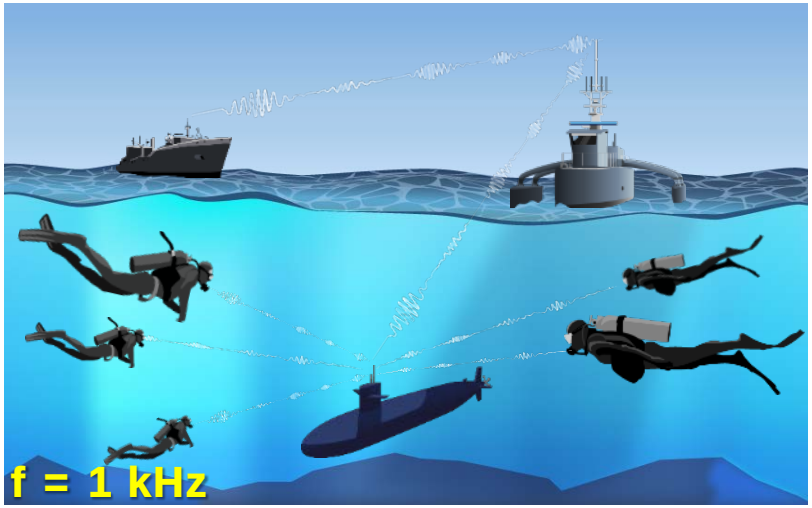
-70 dBm Sensitivity at 8.8 nW, 11 Months into the Program

Improve Sensitivity at Unprecedented Power Levels

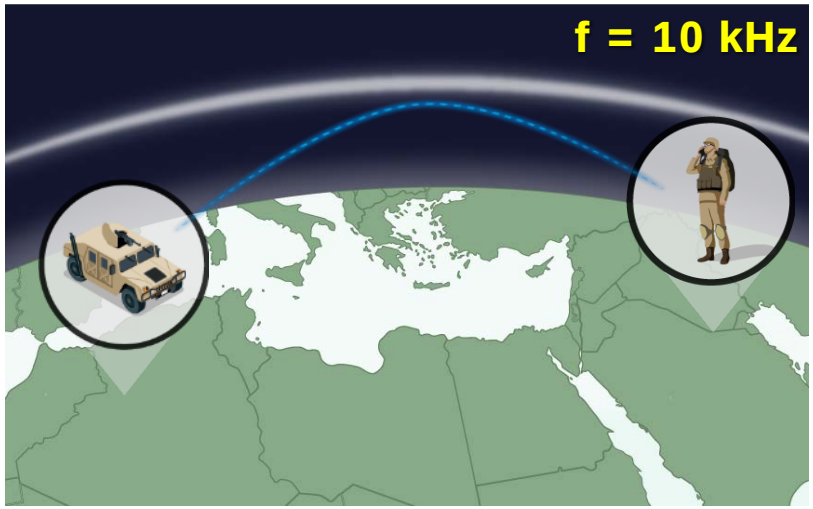
Electromechanical Transmitters for Very Low Frequency RF



Voice: ~500 bps at 1 km range



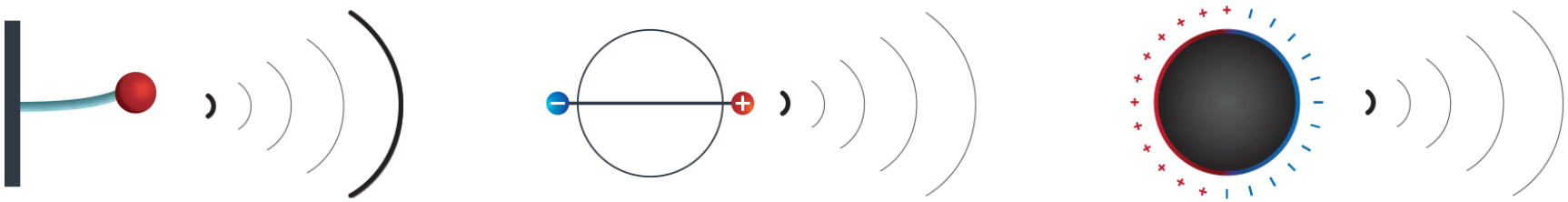
Text Messaging: ~ 10 bps at 100-500 m range



Text Messaging : ~10 bps at 5,000 km range

- **Low bandwidth, but reliable, penetrating and hard to jam!**
- RF-denied environments: underwater and underground
- Long-range communications
- GPS denied environment: localization and timing
- **Sensitive receivers exist, but efficient transmitters are a challenge!**

Portable, Highly Efficient RF Transmit Antennas for the 1-30 kHz Frequency Band



- Oscillatory motion of electric charge is equivalent to an AC current
- Monopole and dipole antennas can be realized in linear or rotational configurations
- Sensitive receivers exist – focus is on transmitters
- Transmitters are highly scalable through modern MEMS manufacturing techniques

- Efficient transmission in a compact package ~ 10^5 smaller than SOA by volume
- Bi-directional link with a mechanical transmitter and a sensitive magnetometer

VLF Transmitter Focus Areas

FEATURES of the approach:

- High **radiation efficiency** through mechanical impedance matching
- Useful **data rate** through direct antenna modulation

TECHNICAL CHALLENGES:

- Materials
  - High charge density
  - Long-term stability
- Mechanical Drive
  - Low-loss, high quality factor, modulation approaches
- System Scaling
  - Large arrays of uniform MEMS devises
  - Synchronization

Workshop held 8/12/16 - http://go.usa.gov/xWnbG - DARPA SN-16-51

RFI closed 9/2/16 - http://go.usa.gov/xWbNW - DARPA-SN-16-55

DARPA

www.darpa.mil

New Frontiers in Communications Electronics

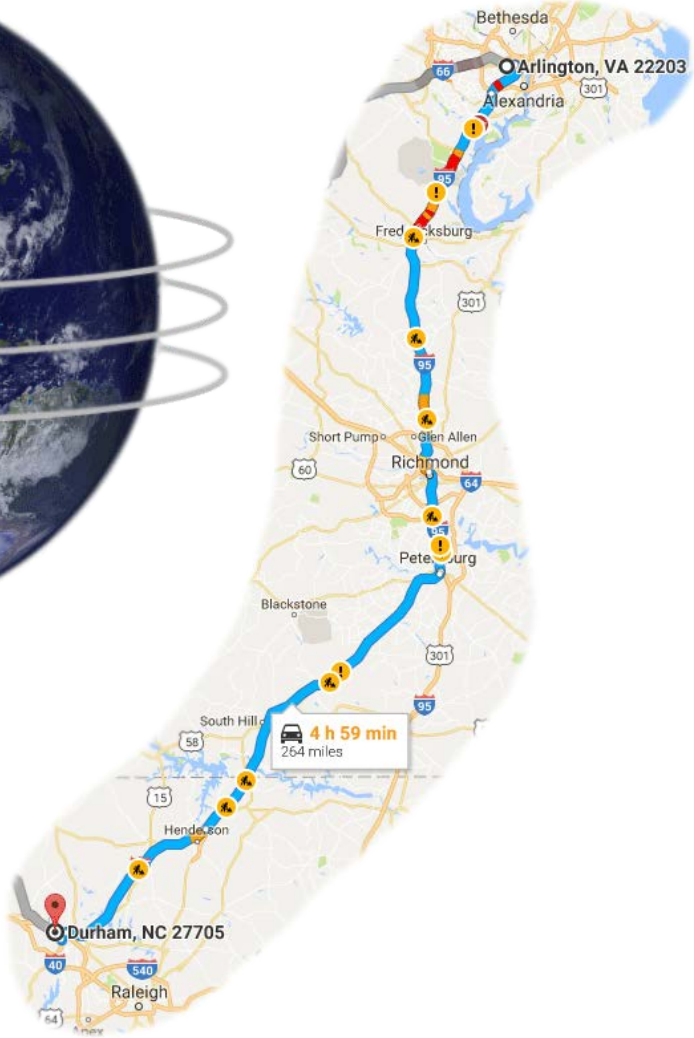
Dr. Dev Palmer
Program Manager
Microsystems Technology Office

Proposers Day

September 20, 2016

Distribution A: Approved for public release

Four years in at DARPA ...



Teleportation is the answer!

DISCLAIMER: DARPA has no current programs on teleportation.

Image sources: Author, NASA, Google Maps

DISTRIBUTION STATEMENT A. Approved for public release; distribution is unlimited.

How much information is in the human body?

tcaaagtaagttagataaacatgatcattcacaggtcagatgttttaaaaaaaaatcattatggtgtacatcacatgtagacaatacttcagaattcatc
tggactaccagaattgagttacctagtacttctcaattctattttaccctaacgtctaataaataacaagtactctagcctcttcgttttatgattcctc
taggaaaagttaatgttacggcccaatcactttttttaacagcccaaacaacatatattagctccaaatatcatttttcccctagaatattctcaacct
attgtccactcaaaacgtgacaaatggaggtctaaagggagaccatacttgactcattttagagctaggatcagacagagtagatttttgccataactc
cttgtaaatgtattcacatttcattcccaagaaaaatagactgatgaagaaatatatcagatatgacaaggccgtgtcgtttaggttacgtaactctaca
aggtttagggtctcaatataaacacacaaagcagatagaagaagcaaaccattcacaatcagacaATGACATCTCTCCATACGTTACTCTTCTCTTCTCT
TCTTTTCTTCATCGTCTTTCCAACCTTCACGTTTTCCTCCACCTTATTGTTTCAGgttcgtctttagttttgcttctttacatacacagactctacacac
tcacttattgggtttctttcaattgtgaaacagAGTTTCAATTGGGAGTCATGGAAGAAAGAAGGAGGATTCTACAATTCTCTCCACAACTCCATTGACG
ACATAGCCAACGCTGGAATCACTCATCTTTGGCTTCCTCCTCCTTCTCAATCCGTTGCTCCTGAAGgttccatttctgctttactctttacacattcaca
taccaatcttgttactcacgcaatcttcattcctcagGTTACTTACCGGGAAAGCTATACGATCTAAACAGCTCCAAATACGGTTCAGAGGCGGAACTGA
AATCGTTAATCAAAGCGTTGAATCAAAAAGGAATAAAAGCTTTGGCTGATATAGTGATTAACCACAGAACAGCTGAGAGGAAAGACGATAAATGTGGATA
CTGTTATTTCGAAGGTGGGACTTCCGATGATCGTCTTGATTGGGATCCTTCCTTTGTCTGCCGCAATGACCCTAAATTTCCCGGTACCGGAAACCTCGAC
ACCGGAGGAGATTTTGATGGAGCGCCCGACATCGACCACCTTAACCCTAGAGTTCAGAAAGAGTTGTCCGAATGGATGAATTGGCTTAAAACTGAAATCG
GATTCCATGGTTGGAGATTTGATTATGTTCGAGGTTATGCATCTTCCATCACCAAATTATACGTTCAGgtaaatcacatatgaattctcaaatatcagac
aacagtattagtatataagaaacataggttgagataattatttactattagtatatataagtatcataggttgatagggttatttactactatttagtat
ataagaaacataagtcaatgcaatcaataagaaatatataagaaagttcactactgattatgtgataaattcctctgtttttggatacacagAATACATC
ACCGGATTTTGCGGTGGGTGAGAAATGGGACGATATGAAGTACGGAGGAGACGGGAAACTAGACTATGATCAGAACGAGCATCGGTCGGGTCTCAAACAG
TGGATCGAGGAAGCGGGTGGTGGTGTGTTGACAGCTTTTGATTTCACCACCAAAGGGATCTTACAGTCTGCTGTCAAAGGTGAGCTTTGGAGACTAAAGG
ACTCGCAGGGAAAACCGCCTGGTATGATAGGAATCATGCCCGGAAACGCTGTCACATTCATAGATAACCATGATACATTCAGAACGTGGGTTTTCCCTTC
TGATAAAGTCTTGCTTGGATACGTTTATATACTTACTCATCCAGGAACTCCTTGCATTgtaagtatcattttagtatgtagctatactatttacaactac
aatcttgttgatatgttatttttgttgcagTTTTATAATCATTACATAGAATGGGGACTAAAAGAGAGCATCTCAAAGCTGGTGGCTATCAGGAACAAAA
ATGGGATTGGTAGCACAAGCTCTGTAACGATAAAAGCGGCAGAGGCGGATCTCTACTTGGCTATGATTGATGATAAAGTTATCATGAAGATTGGACCAAA
GCAAGATGTGGGAACACTTGTTCCTTCTAATTTTGCTTTAGCTTATTCAGGCCTTGACTTTGCTGTCTGGGAGAAGAAGTAAcgcataactcgaatcata
agaaaagtaatcgaatgtatcttcttccttttaataaaacattttggcagtatctaaagatatgtataatgaaatataaaatgataaagaatacctaaa
taaaaagagcactagtggtgttaaaggatacaactccagtgaaagaaaagagttcaagtgaagaagtgtcaacttgtagaaataagtattggaaagtttc
catcgttttgttttgttgcatacaactaatatattatatattggccgactcgtataagatttggagccctactaaaatcagaattatgatgtcttaacca
cacaatactgccaaaatcagaacgaattatattattgtagaagaagaaaaaaaaagtatggtgggaagtgggaacagttagacaggtaaattcgaataaa
tggactaccagaattgagttacctagtacttctcaattctattttaccctaacgtctaataaataacaagtactctagcctcttcgttttatgattcctc
taggaaaagttaatgttacggcccaatcactttttttaacagcccaaacaacatatattagctccaaatatcatttttcccctagaatattctcaacct
attgtccactcaaaacgtgacaaatggaggtctaaagggagaccatacttgactcattttagagctaggatcagacagagtagatttttgccataactc
cttgtaaatgtattcacatttcattcccaagaaaaatagactgatgaagaaatatatcagatatgacaaggccgtgtcgtttaggttacgtaactctaca
aggtttagggtctcaatataaacacacaaagcagatagaagaagcaaaccattcacaatcagacaATGACATCTCTCCATACGTTACTCTTCTCTTCTCT
TCTTTTCTTCATCGTCTTTCCAACCTTCACGTTTTCCTCCACCTTATTGTTTCAGgttcgtctttagttttgcttctttacatacacagactctacacac
tcacttattgggtttctttcaattgtgaaacagAGTTTCAATTGGGAGTCATGGAAGAAAGAAGGAGGATTCTACAATTCTCTCCACAACTCCATTGACG
ACATAGCCAACGCTGGAATCACTCATCTTTGGCTTCCTCCTCCTTCTCAATCCGTTGCTCCTGAAGgttccatttctgctttactctttacacattcaca
taccaatcttgttactcacgcaatcttcattcctcagGTTACTTACCGGGAAAGCTATACGATCTAAACAGCTCCAAATACGGTTCAGAGGCGGAACTGA
AATCGTTAATCAAAGCGTTGAATCAAAAAGGAATAAAAGCTTTGGCTGATATAGTGATTAACCACAGAACAGCTGAGAGGAAAGACGATAAATGTGGATA
CTGTTATTTCGAAGGTGGGACTTCCGATGATCGTCTTGATTGGGATCCTTCCTTTGTCTGCCGCAATGACCCTAAATTTCCCGGTACCGGAAACCTCGAC
ACCGGAGGAGATTT DISTRIBUTIONSTATEMENTAAPPROVEDFORPUBLICRELEASEDISTRIBUTIONISUNLIMITEDAAAACTGAAATCG
GATTCCATGGTTGGAGATTTGATTATGTTCGAGGTTATGCATCTTCCATCACCAAATTATACGTTCAGgtaaatcacatatgaattctcaaatatcagac
aacagtattagtatataagaaacataggttgagataattatttactattagtatatataagtatcataggttgatagggttatttactactatttagtat

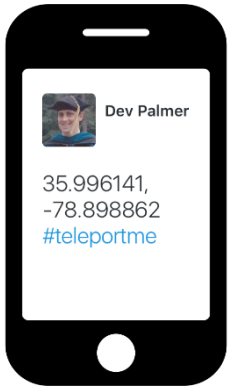
How much is that in bits?

```
0111000110110100110011010110010111101011010111101000000000100001100101100110100010101000011111111101
1111101111000100111001011100010000001011000100100101100100101101001011000011010001100101110001000011
1111011011101100101001001011110100101010101110010110101110011110000111111110010100011011110110101110
1100001001001111010010011001100000100100110100011111111010011101011000101110011111111011011010100 10
1100010111111110100111000110110100110011010110010111110101101011110100000000010000110010110011010001
0101000011111111011111101111000100111001011100010000001011000100100101100100101101001011000011010 00
1100101110001000111111011011101100101001001011110100101010101110010110101110011110000111111110010 10
0011011110110101101100001001001111010010011001100000100100110100011111111010011101011000101110011 11
1111011011010100101100010111111110100111000110110100110011010110010111110101101011110100000000010000
1100101100110100010101000011111111011111101111000100111001011100010000001011000100100101100100101 10
1001011000011010001100101110001000111111011011101100101001001011110100101010101110010110101110011 11
0000111111110010100011011110110101101100001001001111010010011001100000100100110100011111111010011 10
1011000101110011111111011011010100101100010111111110100111000110110100110011010110010111110101101 11
1101000000000100001100101100110100010101000011111111011111101111000100111001011100010000001011000 10
0100101100100101101001011000011010001100101110001000111111011011101100101001001011110100101010101 11
0010110101110011110000111111110010100011011110110101101100001001001111010010011001100000100100110 10
0011111111010011101011000101110011111111011011010100101100010111111110100111000110110100110011010 11
0010111101011010111101000000000100001100101100110100010101000011111111011111101111000100111001011 10
0010000001011000100100101100100101101001011000011010001100101110001000111111011011101100101001001 01
1110100101010101110010110101110011110000111111110010100011011110110101101100001001001111010010011 00
1100000100100110100011111111010011101011000101110011111111011011010100101100010111111110101110010 10
0011011110110101101100001001001111010010011001100000100100110100011111111010011101011000101110011 11
1111011011010100101100010111111110100111000110110100110011010110010111110101101011110100000000010 00
1100101100110100010101000011111111011111101111000100111001011100010000001011000100100101100100101 10
1001011000011010001100101110001000111111011011101100101001001011110100101010101110010110101110011 11
0000111111110010100011011110110101101100001001001111010010011001100000100100110100011111111010011 10
1011000101110011111111011011010100101100010111111110100111000110110100110011010110010111110101101 11
1101000000000100001100101100110100010101000011111111011111101111000100111001011100010000001011000 10
DISTRIBUTIONSTATEMENTAAPPROVEDFORPUBLICRELEASEDISTRIBUTIONISUNLIMITED00100100101100
1001011010010110000110100011001011100010001111110110111011001010010010111101001010100110101110011 11
0000111111110010100011011110110101101100001001001111010010011001100000100100110100011111111010100
```

How hard would that be to transmit?

425 kilometers
55 zettabytes
10 seconds

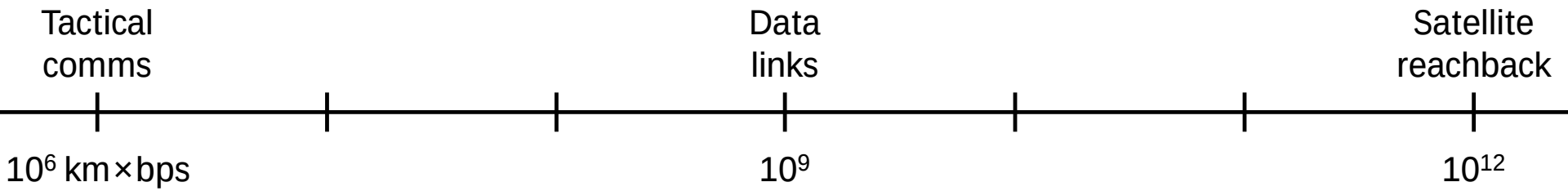
2×10^{25} km × bps



Smartphone image credit: To Uyen, from The Noun Project [CC BY 3.0 us] via Wikimedia Commons

DISTRIBUTION STATEMENT A. Approved for public release; distribution is unlimited.

Range and data rate



$$\mathrm{SNR} = P_t G_t \frac{e^{-\alpha R}}{4\pi R^2} G_r \frac{\lambda^2}{4\pi} \frac{1}{kTBF}$$

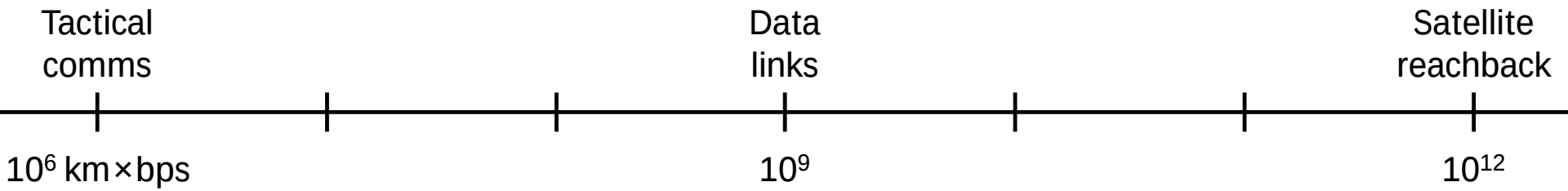
Friis transmission equation

$$C = B \log_2 (1 + \mathrm{SNR})$$

Shannon's Law

DISTRIBUTION STATEMENT A. Approved for public release; distribution is unlimited.

Range and data rate



Range

$$\mathrm{SNR} = P_t G_t \frac{e^{-\alpha R}}{4\pi R^2} G_r \frac{\lambda^2}{4\pi} \frac{1}{kTBF}$$

Friis transmission equation

Data rate

$$C = B \log_2 (1 + \mathrm{SNR})$$

Shannon's Law

DISTRIBUTION STATEMENT A. Approved for public release; distribution is unlimited.

Bandwidth

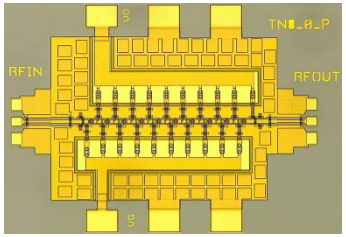
RF | microwave | millimeter-wave

10^6 km×bps | 10^9 | 10^{12}

Higher operating frequency increases bandwidth

$$\mathrm{SNR} = P_t G_t \frac{e^{-\alpha R}}{4\pi R^2} G_r \frac{\lambda^2}{4\pi} \frac{1}{kTBF}$$

$$C = B \log_2 (1 + \mathrm{SNR})$$



Terahertz Electronics (THz)

Solid-state and vacuum electronic components with gain and output power above 1,000,000,000,000 Hz

Image source: Northrop Grumman Corporation

DISTRIBUTION STATEMENT A. Approved for public release; distribution is unlimited.

Power

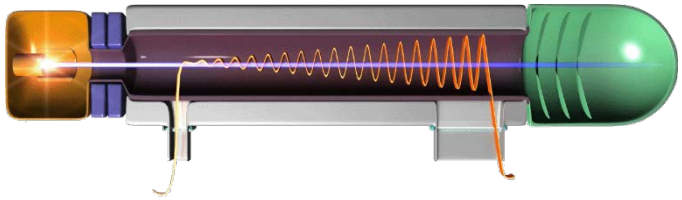
1 kW | 100 W | 10 W

10^6 km×bps | 10^9 | 10^{12}

Higher transmit power increases range

$$\mathrm{SNR} = P_t G_t \frac{e^{-\alpha R}}{4\pi R^2} G_r \frac{\lambda^2}{4\pi} \frac{1}{kTBF}$$

$$C = B \log_2 (1 + \mathrm{SNR})$$



Innovative Vacuum Electronic Science and Technology (INVEST)

Advancing the science and technology base for the next generation of vacuum electron devices operating at frequencies above 75 GHz

Image source: DARPA

DISTRIBUTION STATEMENT A. Approved for public release; distribution is unlimited.

Aperture gain

2 dBi — 60 dBi

10^6 km×bps — 10^9 — 10^{12}

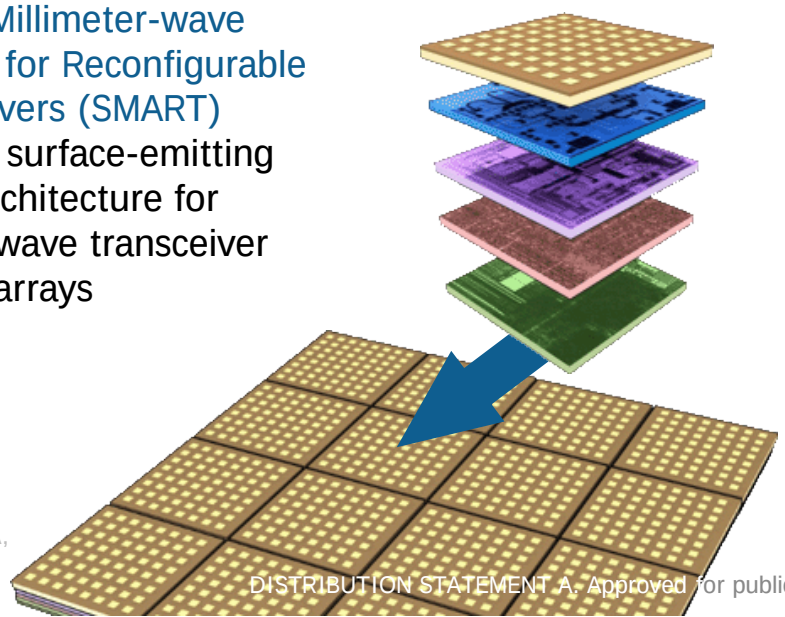
More antenna aperture increases range

$$\mathrm{SNR} = NP_t NG_t \frac{e^{-\alpha R}}{4\pi R^2} NG_r \frac{\lambda^2}{4\pi} \frac{1}{kTBF}$$

$$C = B \log_2 (1 + \mathrm{SNR})$$

Scalable Millimeter-wave Architectures for Reconfigurable Transceivers (SMART)

Integrated, surface-emitting panel architecture for millimeter-wave transceiver arrays



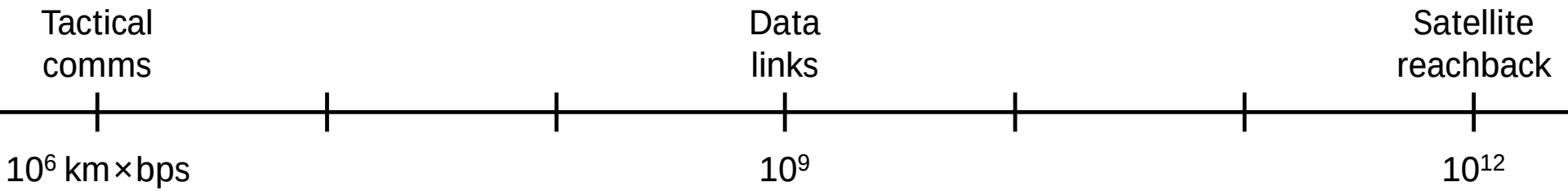
Efficient Linearized All-Silicon Transmitter ICs (ELASTx)

Monolithic, high power added efficiency (PAE), high linearity, millimeter-wave, silicon-based transmitter integrated circuits

Image sources: DARPA, Northrop Grumman Corporation, US Mint

DISTRIBUTION STATEMENT A. Approved for public release; distribution is unlimited.

The future



$$\mathrm{SNR} = NP_t NG_t \frac{e^{-\alpha R}}{4\pi R^2} NG_r \frac{\lambda^2}{4\pi} \frac{1}{kTBF} \qquad C = B\log_2(1+\mathrm{SNR})$$

Think about what we cannot do today

Identify the underlying physics and phenomenology

Determine which knobs you can twist

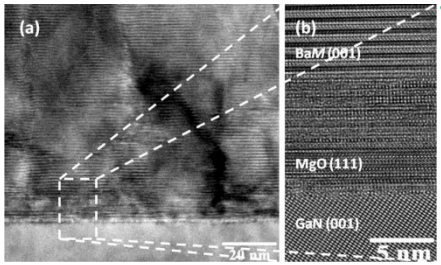
Find ways to twist those knobs

DISTRIBUTION STATEMENT A. Approved for public release; distribution is unlimited.

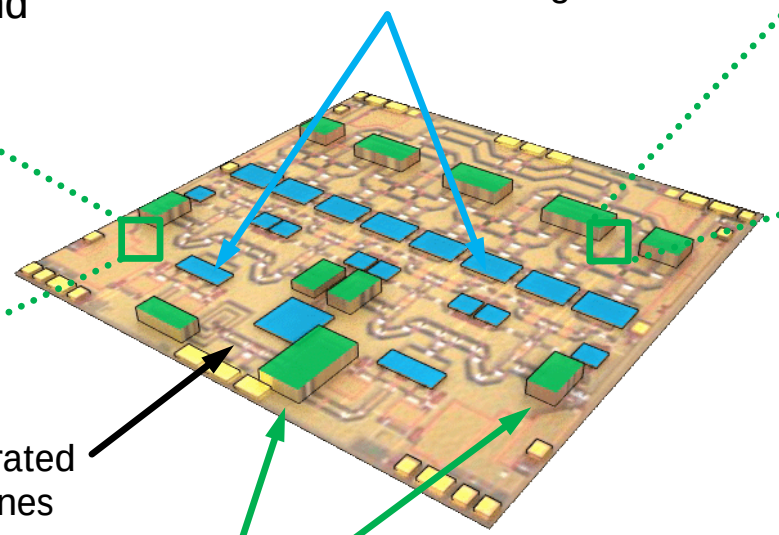
Magnetic Miniaturized and Monolithically Integrated Components (M3IC)

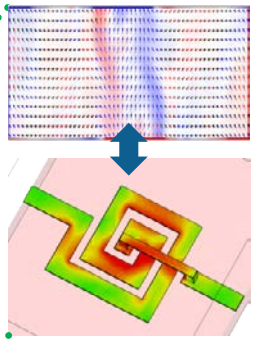
M3IC-enabled RF module-on-chip

TA1: Thick film growth and patterning for microwave and mm-wave components



Same high-performance semiconductor technologies





TA2: System-level modeling of micromagnetic physics

$$\lambda = \frac{1}{\sqrt{\mu\epsilon f}}$$

Compact, integrated transmission lines

Integrated magnetic components distributed throughout the circuit

$$\mathrm{L} = \mu \mathrm{F}(\mathrm{g})$$

Spin waves

$$\theta = VBd$$

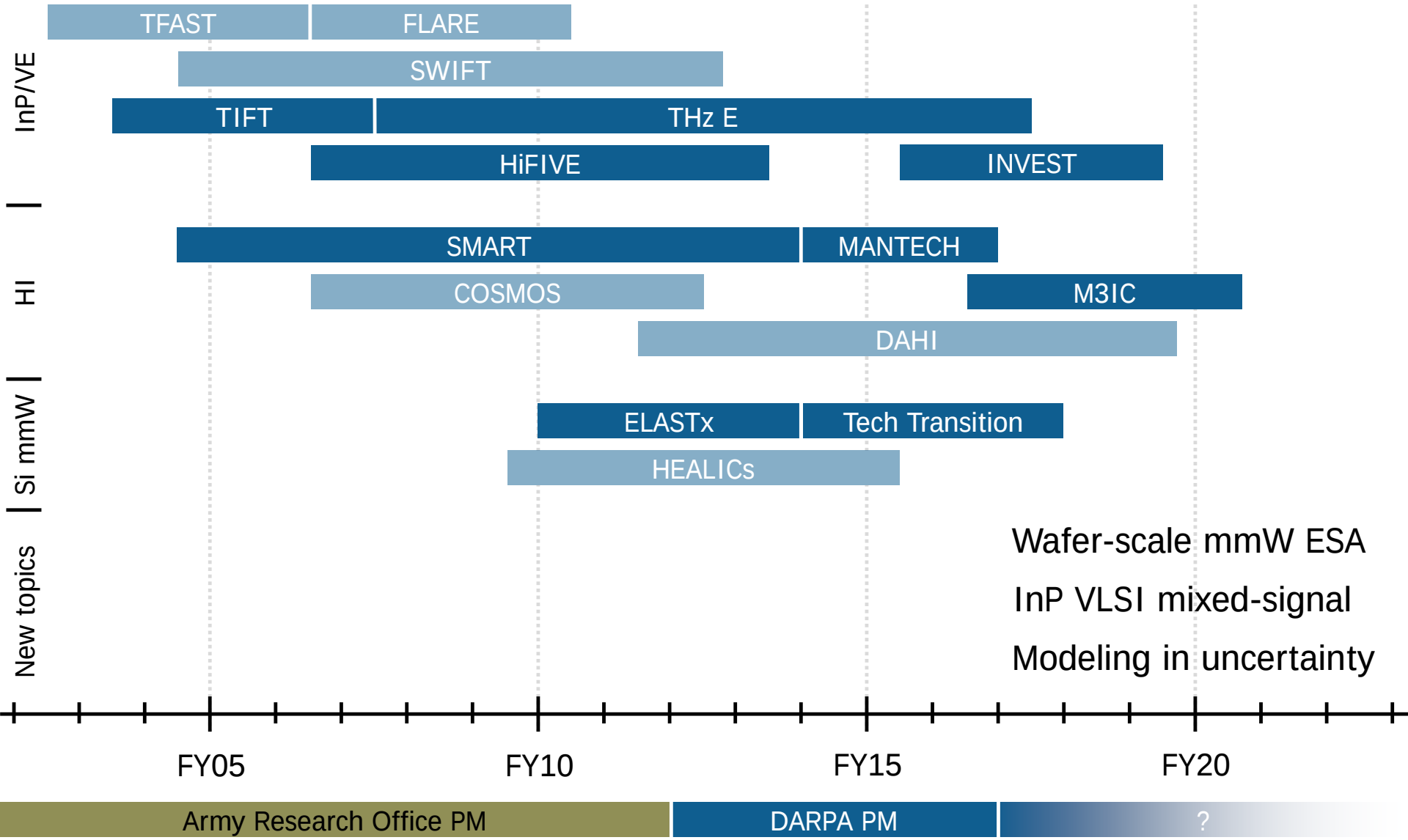
TA3: Magnetic component optimization – new functionality in smaller form factors

Seamless co-design of integrated magnetic materials and semiconductors will enable reduced MMIC size, increased bandwidth, and improved stability and power efficiency

Image sources: DARPA, COMSOL, NIST, Northeastern University

DISTRIBUTION STATEMENT A. Approved for public release; distribution is unlimited.

Timeline



DISTRIBUTION STATEMENT A. Approved for public release; distribution is unlimited.

New frontiers in communications electronics

Access to new regions of the electromagnetic spectrum

More functionality in smaller packages

More output power and power efficiency at higher frequencies

Modular, scalable, multifunctional, and affordable electronically-steered phased array antennas

DISTRIBUTION STATEMENT A. Approved for public release; distribution is unlimited.

www.darpa.mil

Dev Palmer
dev.palmer@darpa.mil

DISTRIBUTION STATEMENT A. Approved for public release; distribution is unlimited.

Intelligence in the RF Spectrum

Paul Tilghman
Program Manager
Microsystems Technology Office

Proposers Day

September 20, 2016

Distribution A: Approved for public release

A little bit about me…

- Not the “classical” MTO Program Manager…

- Not a circuit designer
- Algorithm “weenie” by trade
  - Background in DSP, wireless comms, and EW

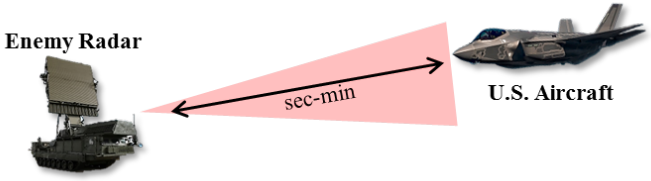
- Became an AI aficionado in 2010 when we started building a new breed of RF systems – Cognitive EW

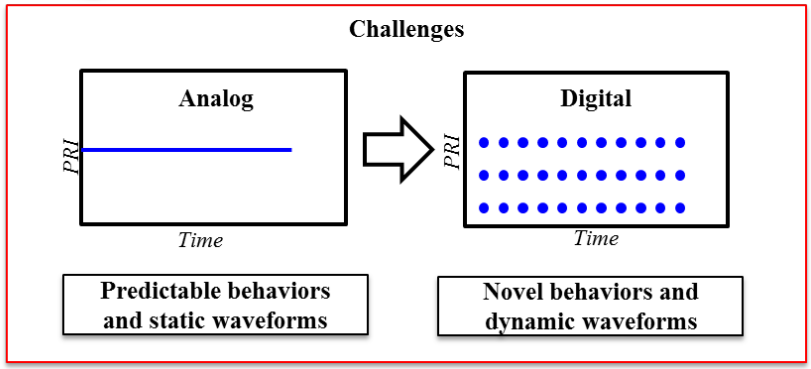
<u>My Mission:</u>
Make wireless systems intelligent, less rigid, and more useful

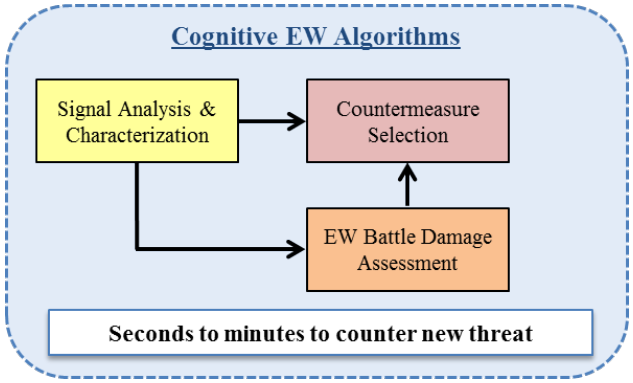
On-going efforts in intelligent RF systems

Cognitive Electronic Warfare

Can we make an existing EW systems smart enough to counter the unexpected?



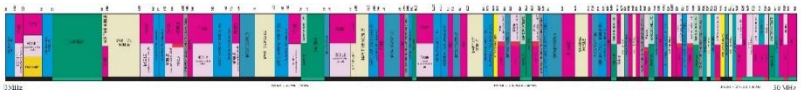




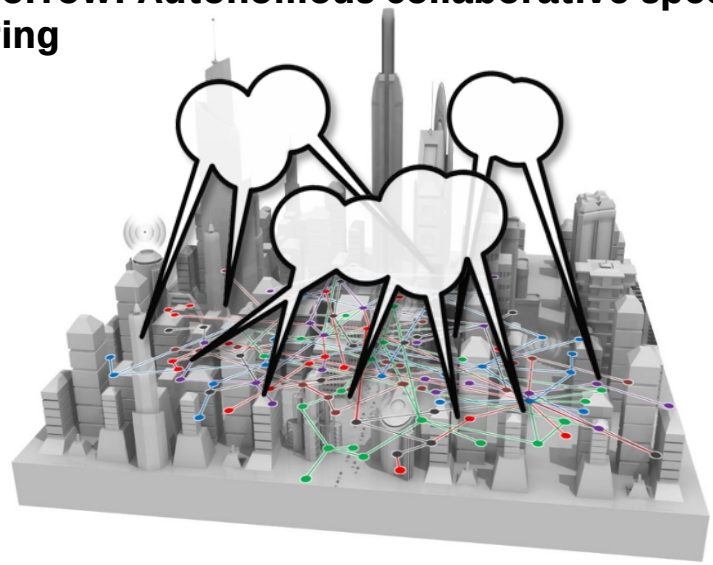
Spectrum Collaboration Challenge

Can multiple radios collaborate and learn to overcome the shared problem of spectrum scarcity?

Today: Management through isolation



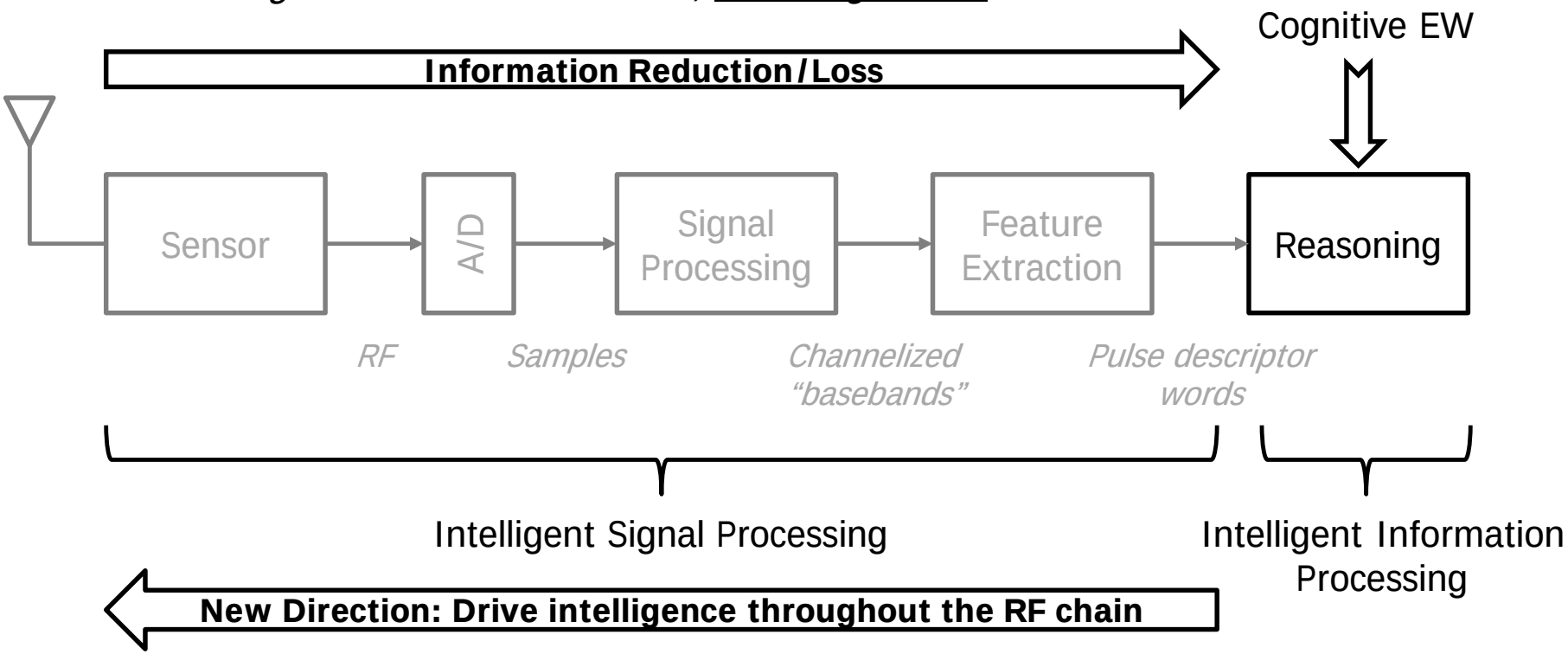
Tomorrow: Autonomous collaborative spectrum sharing



SpectrumCollaborationChallenge.com

New directions in intelligent RF systems
Machine Learning RF Systems

Processing chain is a series of fixed, hand engineered choices

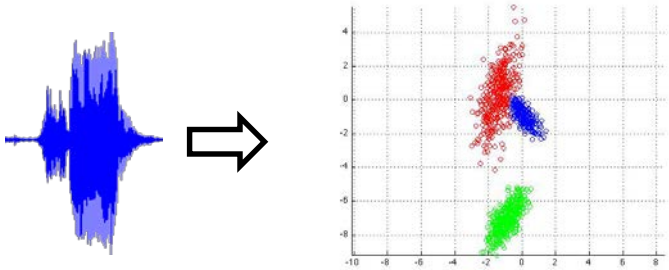
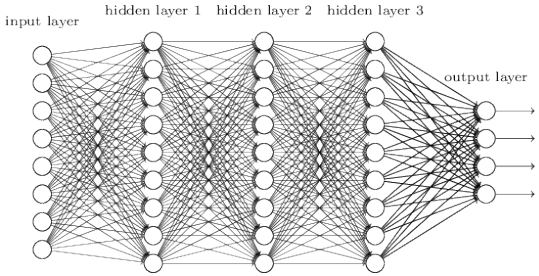
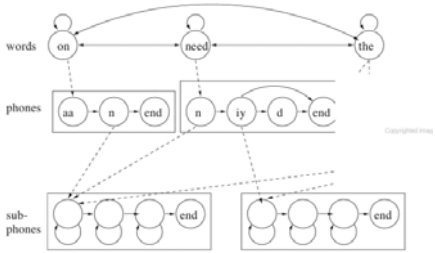
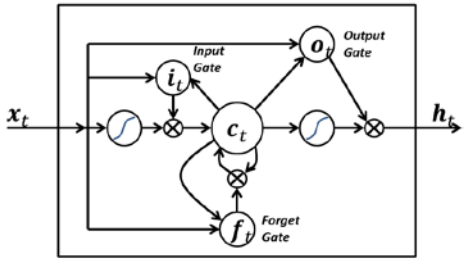


Machine Learning RF Systems (RF-MLS)

- Machine-learned components replace traditional hand-engineer design process
- Exploit adaptability and joint learning throughout the processing chain
- Custom silicon to employ in realistic settings
- **RFMLS outperform classically designed systems**

First vs Second Generation Machine Learning

Hand-engineered vs Machine Learning

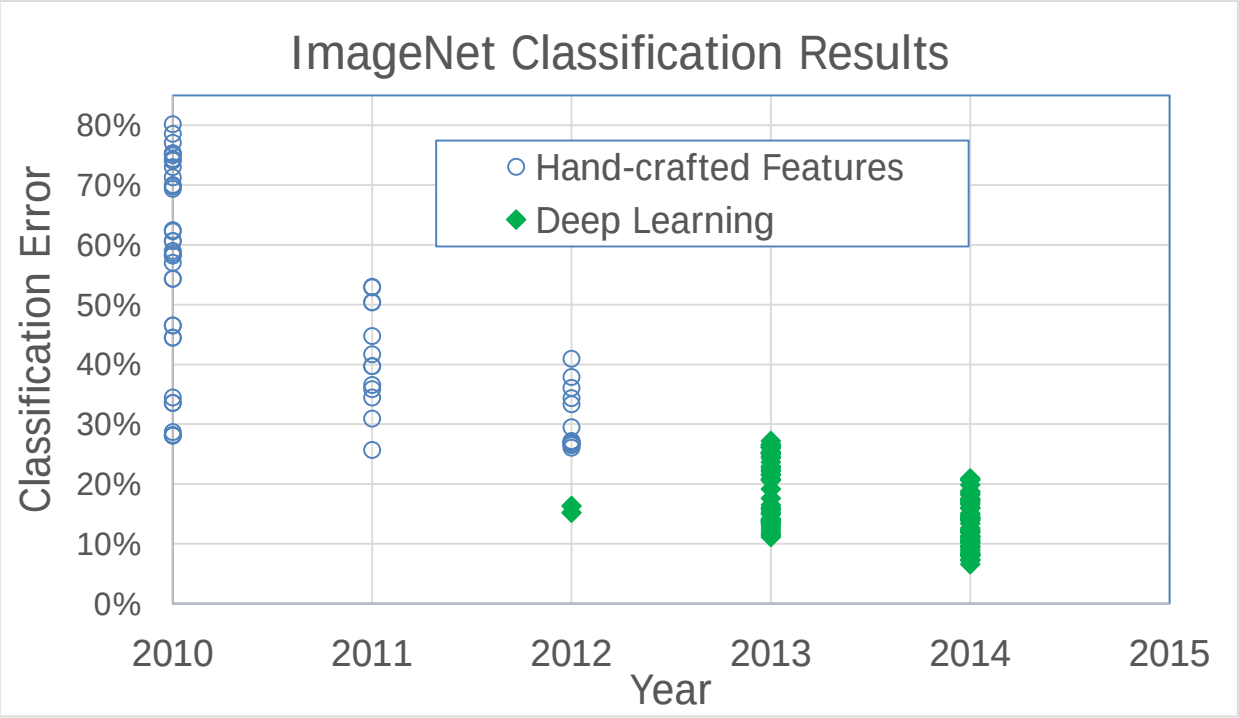
	First Generation	**Second Generation**
	Hand-built features and models	*Learned models from abundant data*
Feature Representation	Gaussian Mixture Models	Deep Neural Networks
		
Sequencing	Hidden Markov Models	Recurrent Neural Networks w/ Memory
		

Most advanced and modern RF systems are 1st generation

Distribution Statement "A" (Approved for Public Release, Distribution Unlimited)

Image Analysis – Impact of 1st to 2nd Generation? Feature Learning Matters

- Deep Learning Approach Wins ImageNet (2012)
- Demonstrates feature learning can outperform hand crafted features



By 2013, all top winners are utilizing Deep Learning Approach (supervised classifier convolutional stacked deep network)

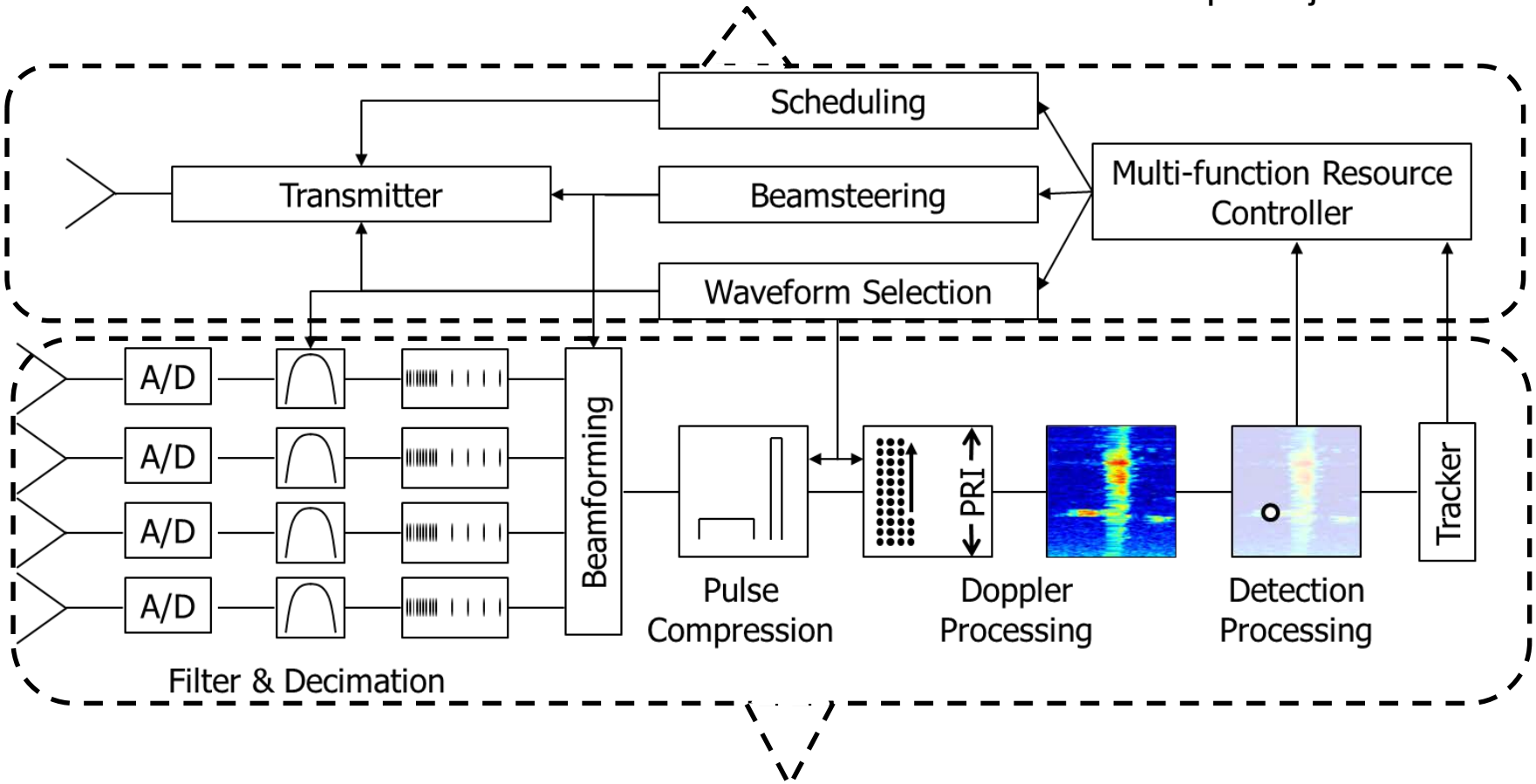
Distribution Statement "A" (Approved for Public Release, Distribution Unlimited)

Example: Generalizable learned radar

Complex radar control

Learn transmit waveforms with give the best discrimination for target and scene

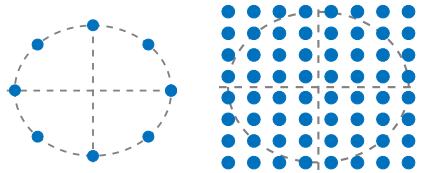
Multi-Function Radar must learn to balance resource allocation across multiple objectives

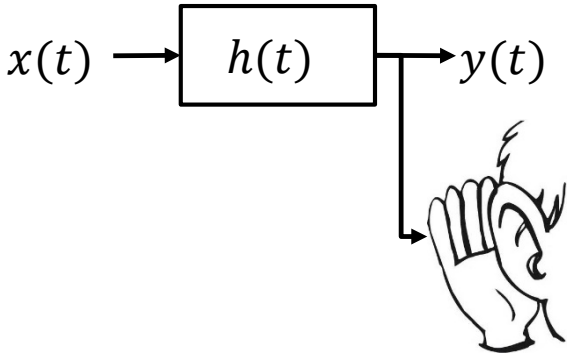


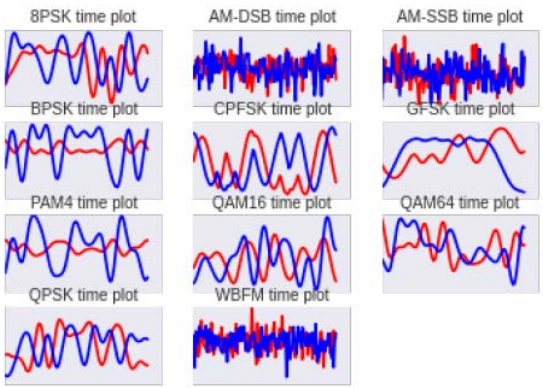
Generalizable radar detection and tracking

Micro-UAV vs Birds, Moving target vs windswept clutter, Semi-submersible vs waves…

Early examples of machine learning for RF



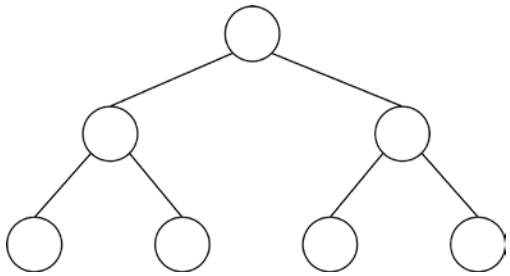


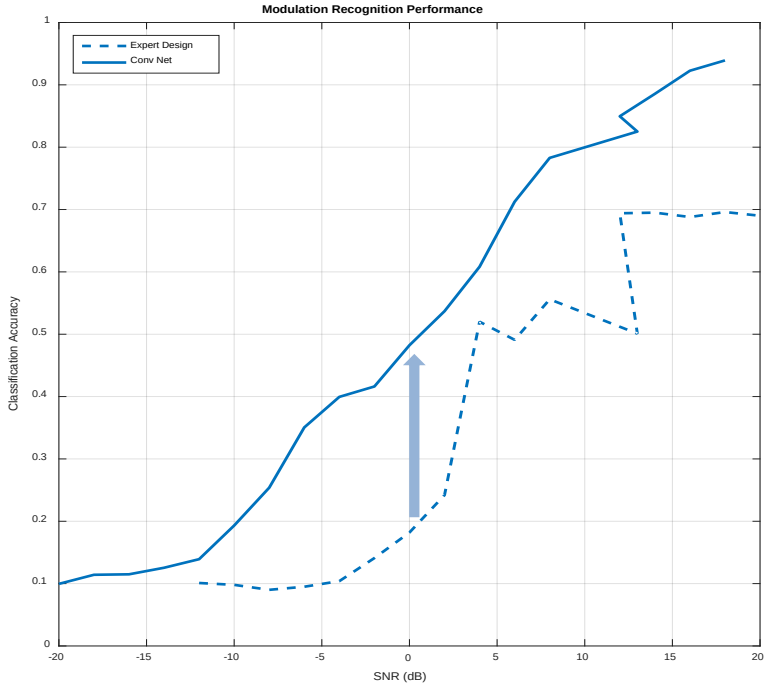


Hand engineered:

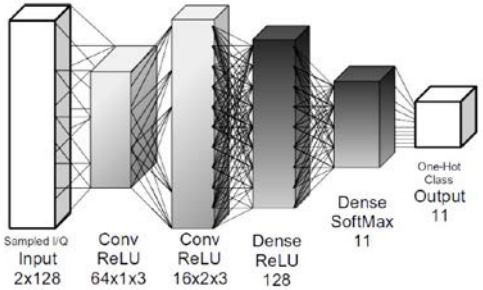
$$\lambda_1, \lambda_2, \ldots$$

$$\Downarrow$$

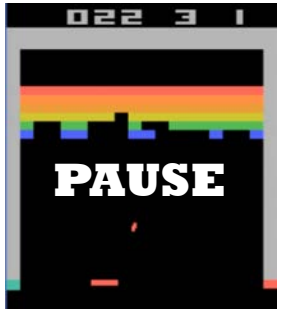
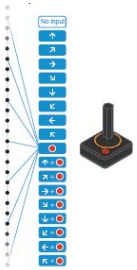




Machine Learned



Unique challenges of applying ML to RF

	Current Applications	RF
Data Volume	IMAGENET 1.2M images = 300GB Deep Speech 2 20k hrs = 1 TB	**Radar** 1kb - 100 Gb per detection = 1 EB!
SNR	**Automated speech recognition** >10 dB SNR	Most problems of interest < 0 dB SNR
Training Active Systems	  18 actions	 1,000,000+ actions
Arch	Deep Networks, emerging recurrent networks	Multi-modal data? Temporally aware.
Hardware	**Training:** GPUs **Evaluation:** Cloud evaluation, small networks in ASICs	**Training:** Is COTS HW up to the challenge? **Evaluation:** Complex networks, in SWAP constrained environments ➔ reconfigurable ASICs

www.darpa.mil