Cognitive Systems

High Performance Embedded Computing Workshop

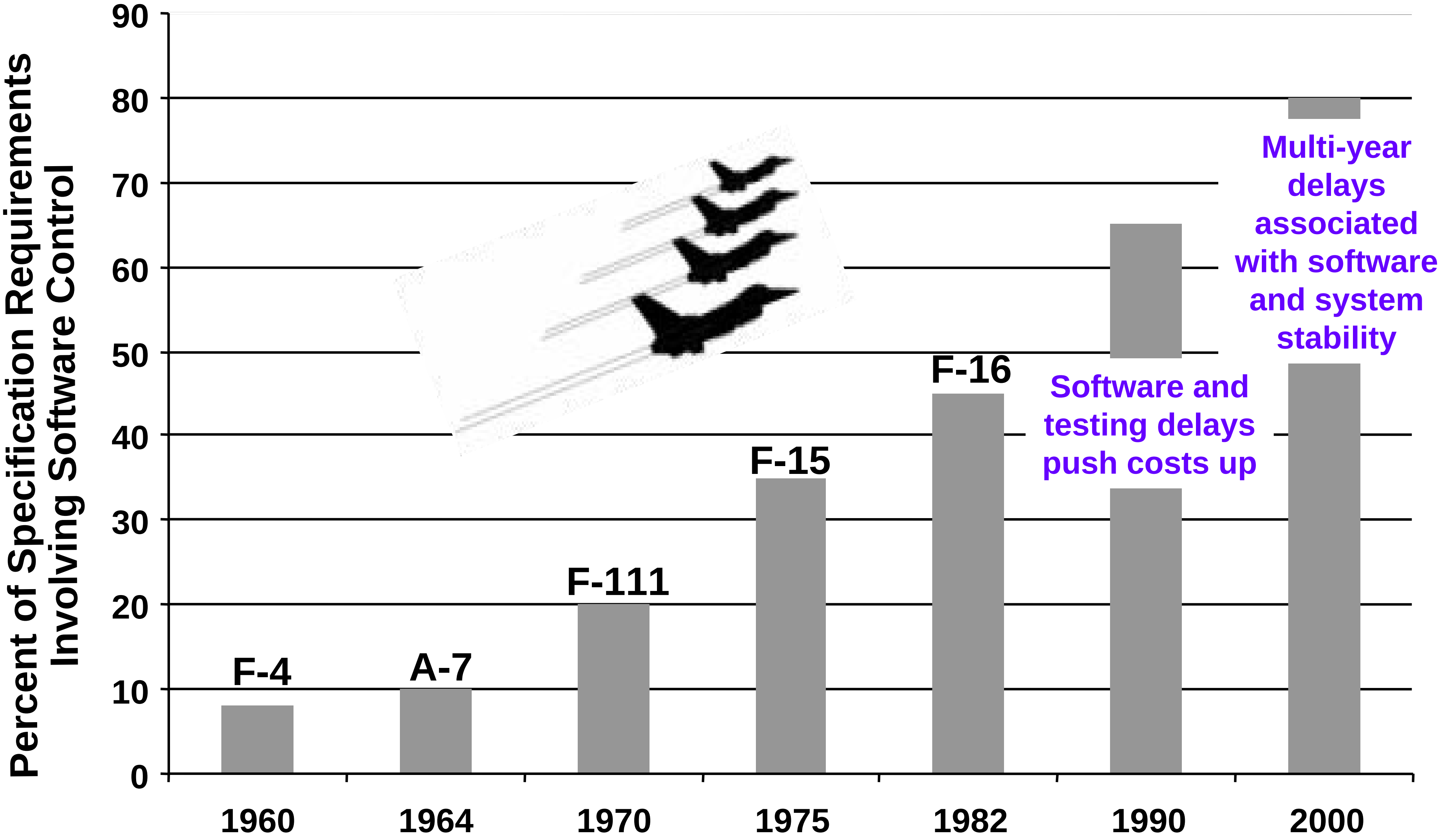
Robert Graybill
DARPA IPTO
Sept 28, 2004

The Challenge

- **Computer systems are the backbone of key national infrastructure and critical DoD systems**
  - **Virtually all important transactions involve massive amounts of software and multiple computer networks**
  - **DoD future vision is "network-centric warfare"**
- **While *computational performance* is increasing, productivity and effectiveness are not keeping up**
  - **Cost of building and maintaining systems is growing out of control**
  - **Systems have short lifespans with decreasing ROI**
  - **Demands on expertise of users are constantly increasing**
  - **Users have to adapt to system interfaces, rather than vice versa**
- **As a result, systems have grown more complex, more fragile, and more difficult to develop**

We need to change the game

Capability Provided by Software in DoD Systems is Increasing but so are the Challenges…



Ref: Defense Systems Management College

IPTO's Approach

Developing Cognitive Systems:

Systems that know what they're doing

- **A cognitive system is one that**
  - **can reason, using substantial amounts of appropriately represented knowledge**
  - **can learn from its experience so that it performs better tomorrow than it did today**
  - **can explain itself and be told what to do**
  - **can be aware of its own capabilities and reflect on its own behavior**
  - **can respond robustly to surprise**

Computing Systems that know what they're doing can…

- …reflect on what goes wrong when an anomaly occurs and anticipate its occurrence in the future
- …respond to naturally-expressed user directives to change behavior or increase functionality
- …be configured and maintained by non-experts
- …reconfigure themselves in response to environmental changes and mission events
- …reduce the effort to develop and maintain software
- …thwart adversarial systems that don't know what they're doing
- …preserve "corporate memory" to ease transitions for rotational personnel

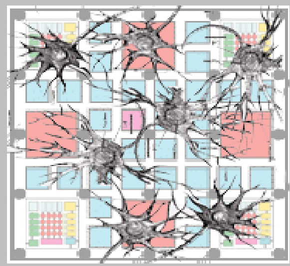
Four Tiers of Agile Processing

Systems That Know What They're Doing

What's Next?

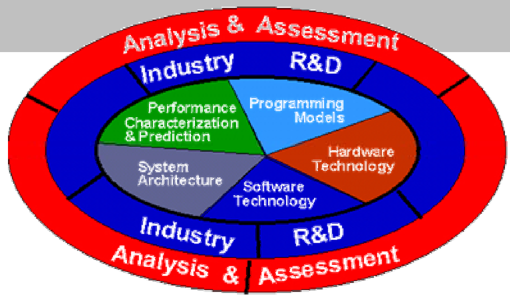
- Intelligent Systems
  - \- Architectures for Cognitive Information Processing (ACIP)

+ Cognitive Processing Hardware Elements SBIRs



- High-End Application Responsive Computing
  - High Productivity Computing Systems Program (HPCS)

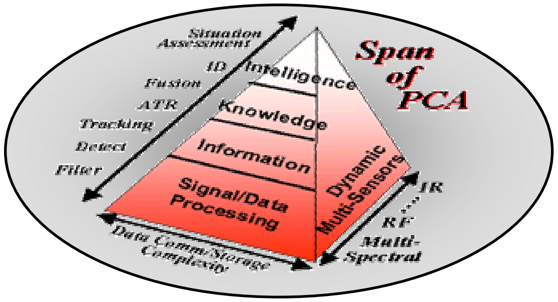
+ HECURA



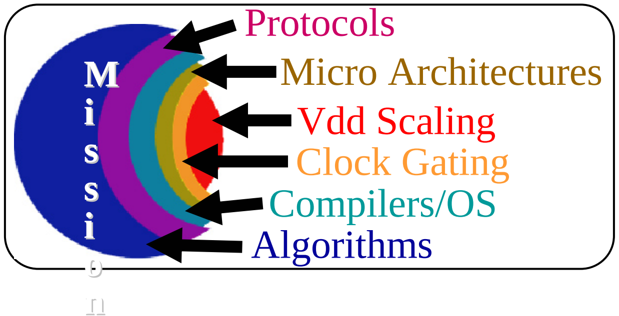
- Mission Responsive Architectures
  - Polymorphous Computing Architectures Program (PCA)

+ OneSAF Objective System

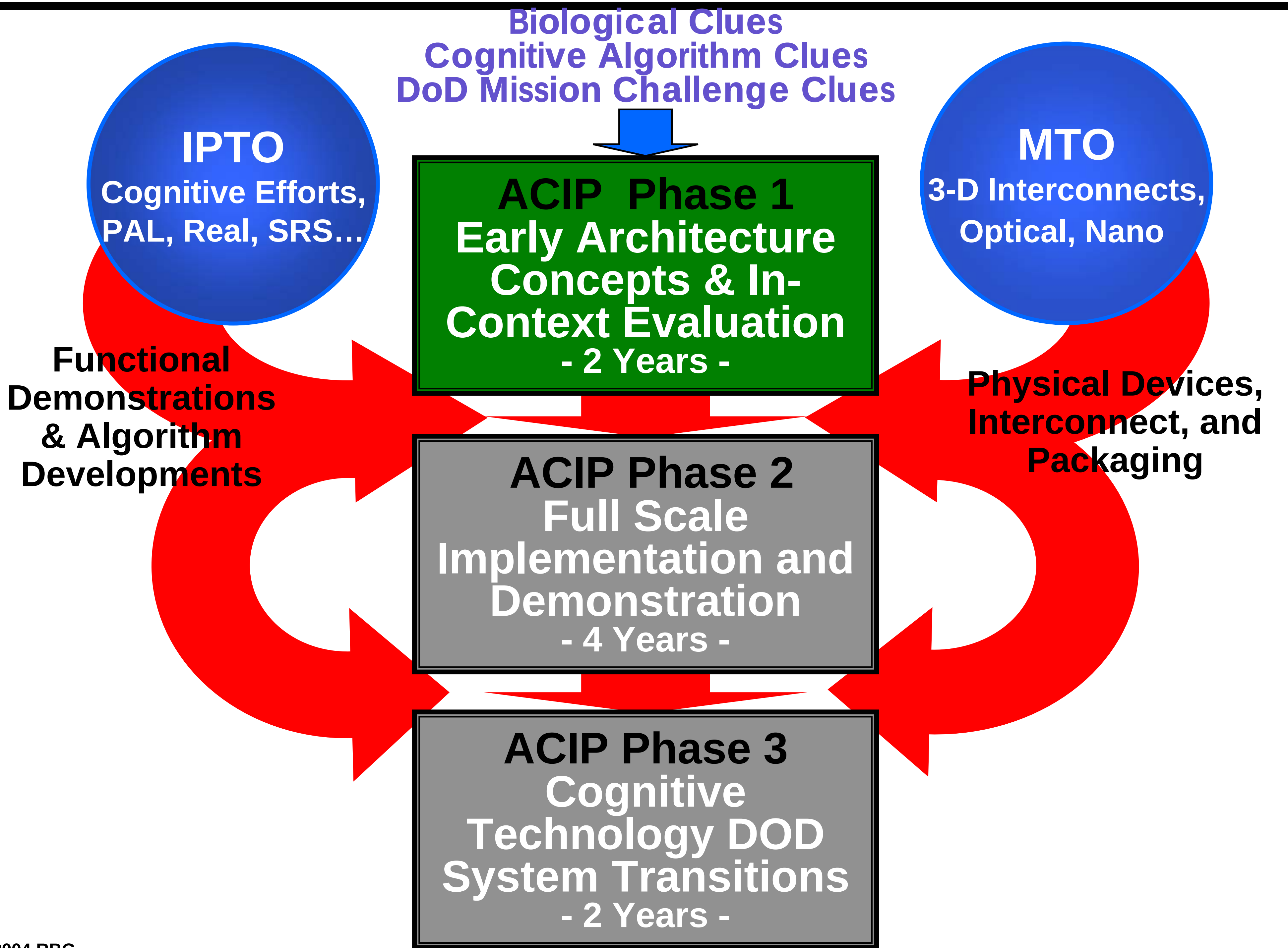
+ XPCA??



- Power Management
  - Power Aware Computing and Communications Program (PAC/C)



ACIP Program Vision



INFORMATION PROCESSING TECHNOLOGY OFFICE

ACIP Phase I

Study Considerations

Cognitive Reasoning, Learning & Knowledge Technologies → Cognitive Processing Requirements

In-Context Cognitive DoD Applications → DoD Applications Requirements & Real-time Constraints

HW/SW Architectures & Technologies → Innovative Architecture Concepts

Multiple Disciplinary Teams

Metric Evaluation

In-Context Evaluations

Analyze Cognitive Techniques, Computing, Memory and Control Requirements

Early Architecture Concepts

Technology Assessments

(2 Year Study)

MTO Technology | IPTO Projects

Deliverables

- System architecture concepts, models, & evaluations-to-SDR
- Concept device specification and technology roadmap
- Cognitive computing requirements, analysis, specifications and runtime characterization
- Living Framework Draft
- Composable runtime concepts
- Phase II Challenge Problem, Metrics, & Go No/Go Definition

ACIP Phase I Response

- **Fantastic Response!!!**
- **Participation Mix (Including Subs)**
  - **9 Defense Contractors**
  - **11 Research Laboratories**
  - **51 Universities**
  - **30 Commercial Companies**

Broad Multi-Disciplinary Coverage required for System Innovation

Large Diverse and Robust Teams Resulted in the Best Concepts

Study Technical Framework Concept has Emerged

Funded ACIP Efforts

- **COGnitive ENGine Technology (COGENT)**
  - **Raytheon Company - Network Centric Systems**

- **Polymorphous Cognitive Agent Architecture (PCAA)**
  - **Lockheed Martin Advanced Technology Labs**

- **CEARCH: Cognition Enabled Architecture**
  - **University of Southern California/ISI**

ACIP Related SBIRs

- Reservoir Labs Inc – Cognitive Processing Hardware and Software elements
- Intelligent Automation Inc. – Hardware Architectures for Flexible Component Based Hybrid Cognitive Systems
- Hoplite Systems LLC – Cognitive Processing Hardware Elements
- Cardinal Research LLC – Cognitive Processing Hardware Elements
- Saffron Technologies – Associative Memory Hardware Elements for Cognitive Systems (Funded by AFRL)

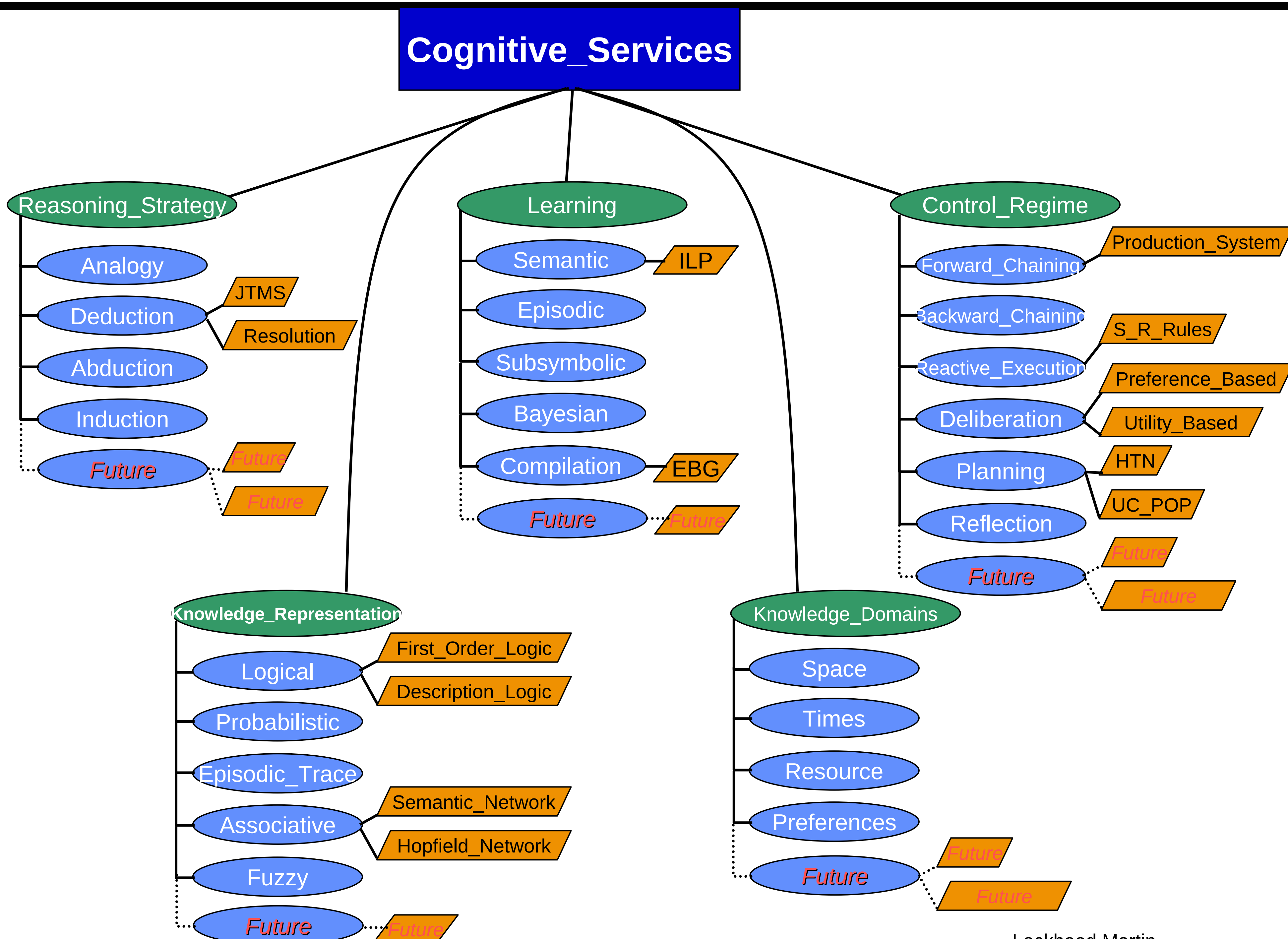
Cognitive Technology Classification

Reasoning Algorithms	Symbolic (S) Probabilistic (P) Hybrid (H)	Ray	LM	ISI
1st Order Reasoning	S		X	
Abductive Reasoning	S,P,H	X	X	
Analogical Reasoning	S,H	X		
Bayesian Networks	P			
Case-based Reasoning	S,H			
Causal Reasoning	P	X		
Common Sense Reasoning	S	X		
Counterfactual Reasoning	S			
Deductive Inference	S	X		
Defeasible Reasoning	H		X	
Forward & Backward Chaining	S			
Fuzzy Reasoning	H		X	
Game Theory - Optimization	H			
Goal-oriented Planning	S			X
Heuristic Meta-reasoning	H			X
Inductive Reasoning	S		X	
Logical Pattern Matching	S			
Logical Unification	S			
Markov Processes	P			
Mathematical Programming	H			
Maximum Likelihood	P	X		
Meta-meta Reasoning	S			X
Modal Intuitionistic, Higher Order Reasoning	S		X	
Model-based Reasoning	H	X		
Non-monotonic Reasoning	S			
Optimal decisions - Min-Max, Auctions	P	X		
Pattern Matching	H			
Probabilistic Constraint Satisfaction	H	X	X	X
Resource-limited Theorem Proving	S		X	X
SAT - Constraint Satisfaction	S	X		
Special Purpose Reasoning Algorithms	S			X
Temporal Reasoning	S,P,H	X		
Utility Theory	P	X		
Well-formedness Reasoning	S			X

Learning Algorithms	Symbolic (S) Probabilistic (P) Hybrid (H)	Ray	LM	ISI
Abductive Learning	H		X	
Abstraction	H	X		
Analogical Learning	S			X
Artificial Neural Networks	P		X	
Associative	H	X		
Bayesian Learning	P		X	
Chunking	H	X		
Classification Learning	H			
Clustering	P,H	X		
Constructing Analogies	S	X		
Co-training	H			
Data Mining	H			
Decision Trees	H		X	
Dimensionality Reduction	H			
Evolutionary Search	H			X
Genetic Algorithms	P		X	
Inductive Learning	S		X	
Instance-based Learning	P		X	
Learning from Advice	H	X		
Network Construction	P			
Parameter Learning	P	X		
Plan recognition	H			
Reinforcement Learning	P,H	X	X	X
Relational Learning	S	X		
Rule Generation Composition & Specialization	S			
Statistical Clustering	P		X	
Statistical Learing (nearest neighbor, approx)	P			X
Supervised Learning	P			X
Support Vector Machine	P	X		

Knowledge Representation Algorithms	Symbolic (S) Probabilistic (P) Hybrid (H)	Ray	LM	ISI
1st Order Logic (with extensions)	S	X		X
Bayesian Classifier	P			
Bayesian Networks	P,H	X		
Case -based	S			X
Causal Networks	H	X		
Conceptual Graphs	H	X		
Decision Trees	H	X		X
Episodic	H		X	
Frames	H	X		
Fuzzy Logic	H		X	
Horn Clause Program	S			
Influence Diagrams	H	X		
Knowledge Acquisition	H			
Logical (Prop., FOL, Frame-based)	S			
Logical Rules	S		X	
Markov Models	P	X		X
Multi-layer Neural Net	P			
Ontologies	H	X		X
Production System	S			
Propositional Logic	H	X		
Reactive Plan	S			
Relational Models	H	X		
Rule-based Systems	H			
Self-knowledge	H			
Semantic Nets	S			
Situation Calculus	S	X		
Taxonomic Hierarchy	P			
Temporal Networks	H	X		
Type Ontologies and Constraints	S			X

Cognitive Services



Cognitive Computing Requires Innovation

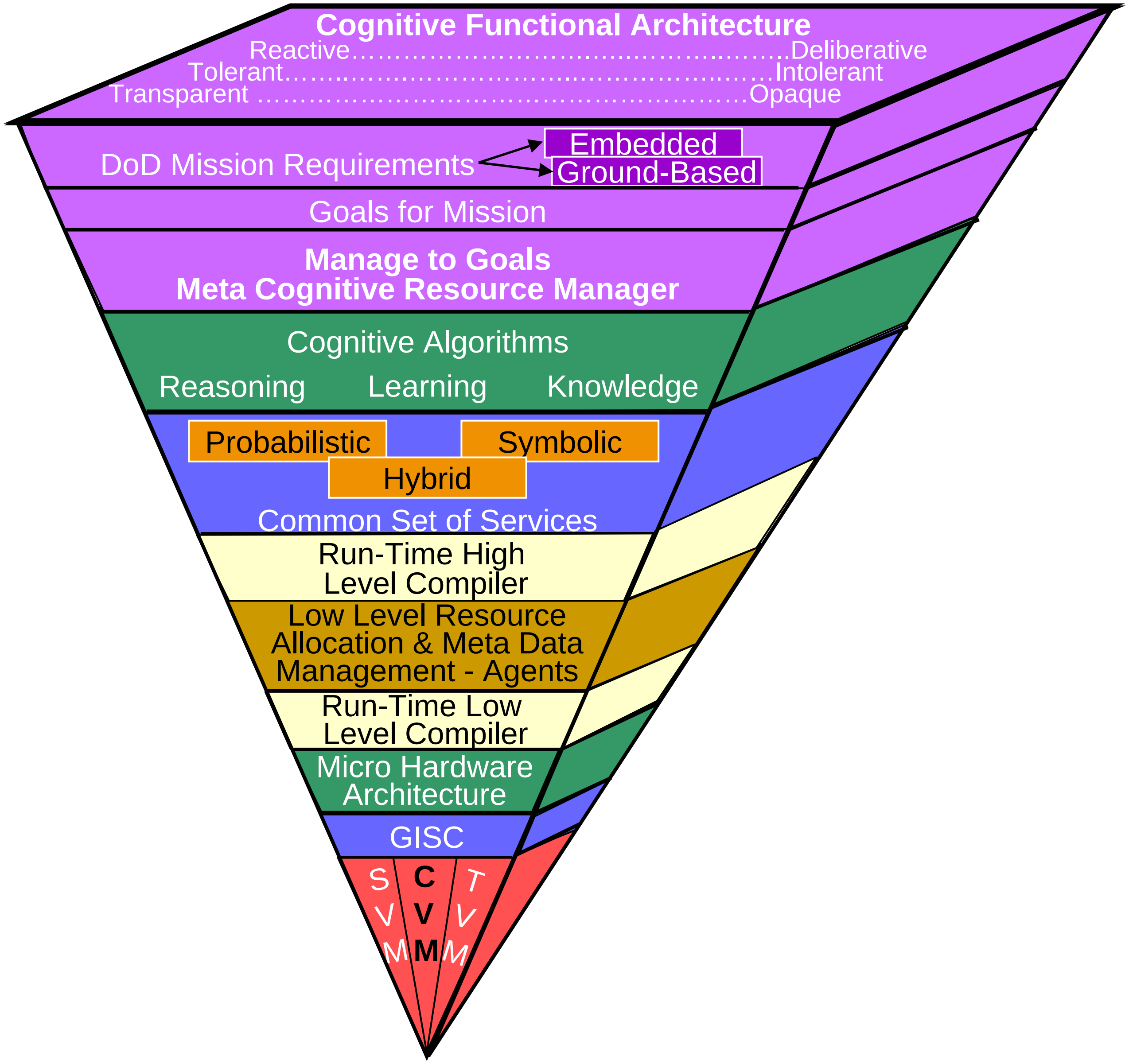
Classical Computing

- Markovian –current state only
- Processor-oriented; favors regular addressing
- Procedural, results oriented – apply this function next
- Key operations: arithmetic & simple scalar decision making
- Single deterministic result
- Parallelism difficult to extract
- Functional composition determined at compile time
- Largely static resource management

Cognitive Processing

- History of prior results guides next: "learning"
- Memory-oriented; unpredictable access patterns, with metadata guiding access
- Goal oriented – with multiple, possibly incompatible objectives,
- Process oriented – history + new perceptions => new knowledge
- Context oriented – computation based on metadata from prior results
- Key operations: wide spectrum including complex pattern matching
- Often multiple "acceptable" results
- Speculation, futures a first class activity
- Functional composition determined at run-time
- Dynamic resource management (Reasoning vs Learning Balance)

ACIP Strawman Framework



PCA (SVM+TVM) + CVM = ACIP???

Potential New Research Ideas!

Leveraging Embedded Computing Workshop Ideas

Chaired by

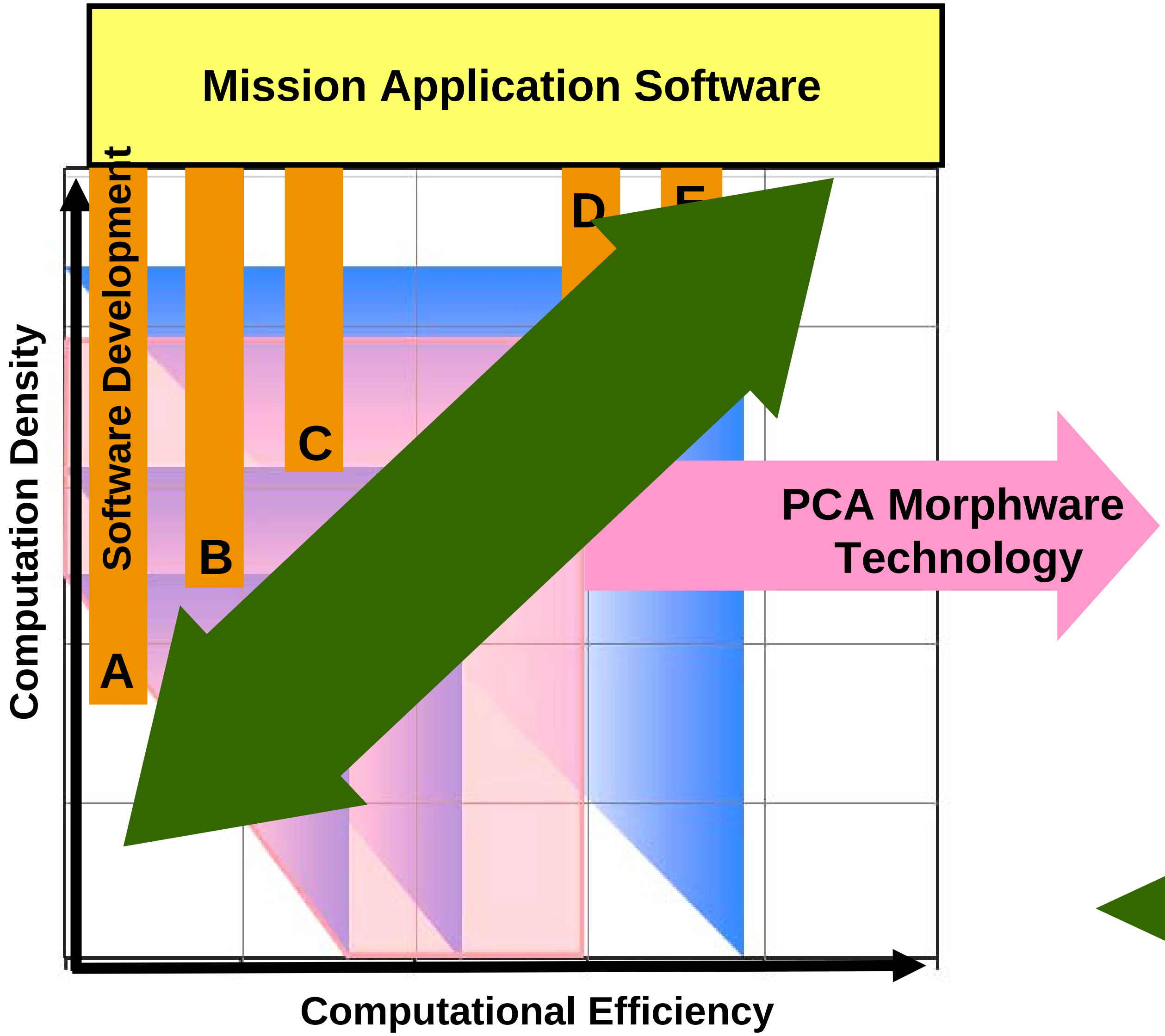
MIT LL and ISI

Future Role of Embedded Computing Devices:

GP, DSP, GPU, NIC, FPGA, ASIC

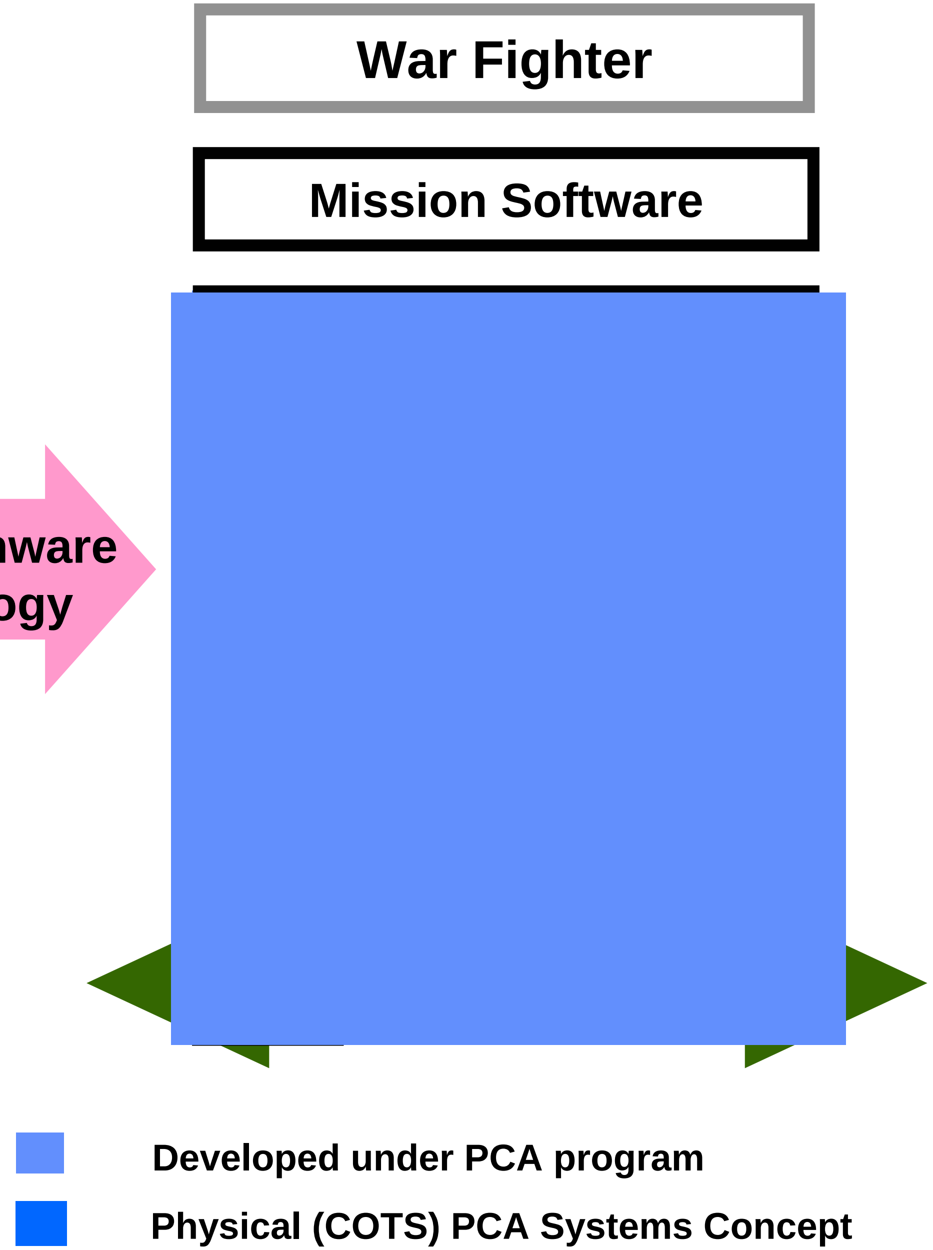
Physical (COTS) PCA Systems

The Problem



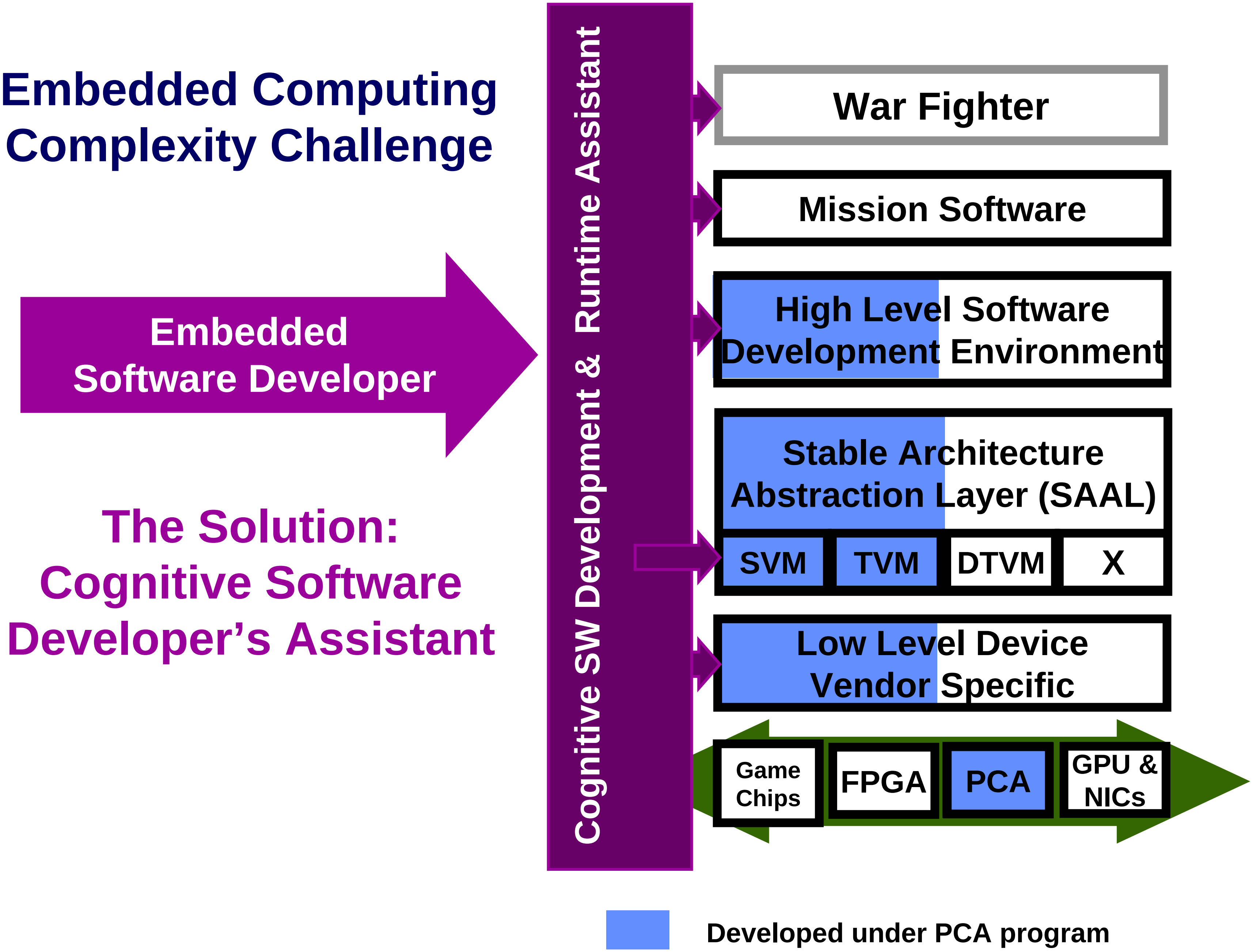
Manual Low Visibility Stove Pipe SW Development Environments

The Solution



Software Developer's Assistant

Embedded Computing Complexity Challenge



The Solution: Cognitive Software Developer's Assistant

The Future is Yours

Become an DARPA Program Manager!!