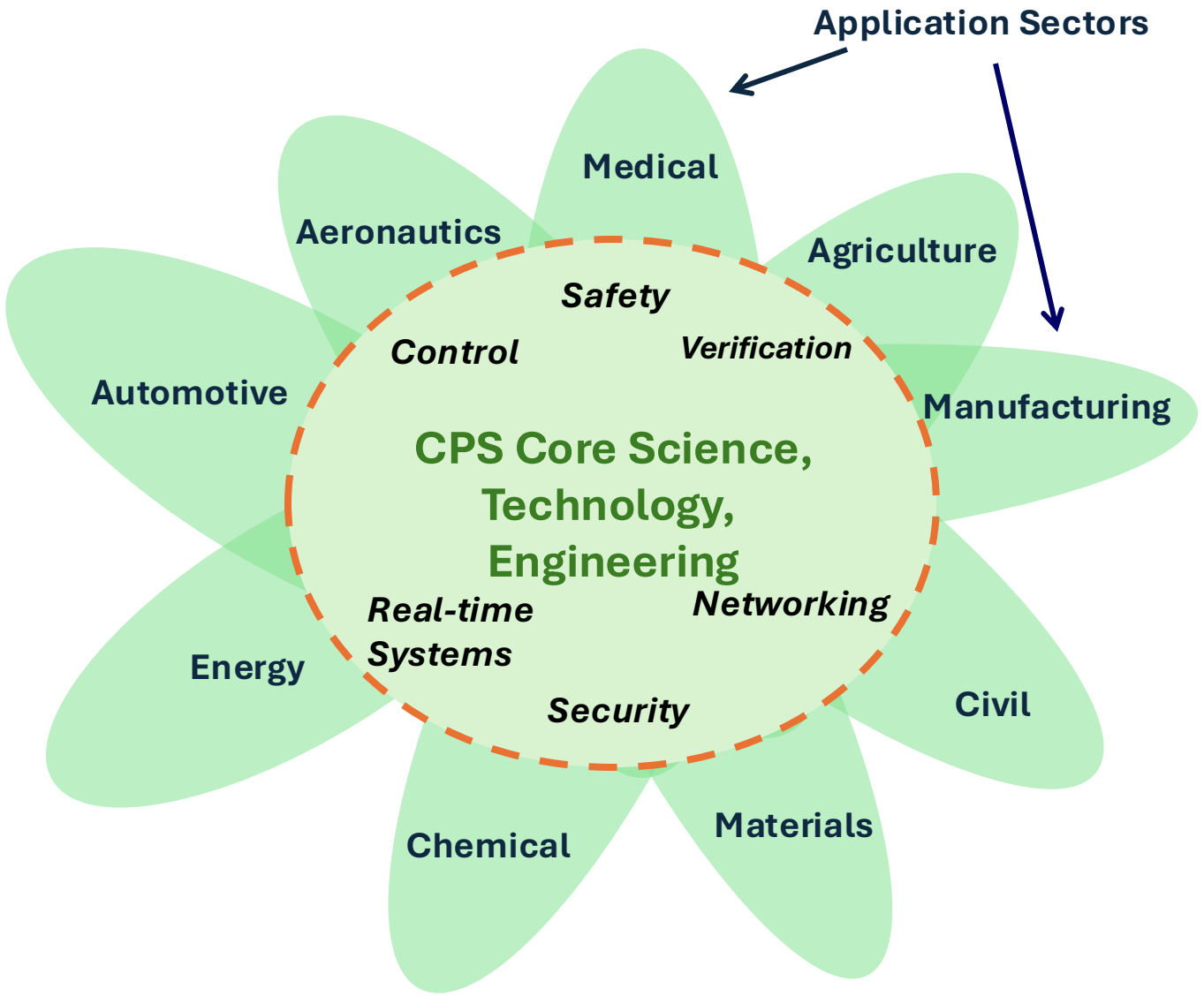
Cyber-Physical Systems



Looking Backwards and Toward the Future

Some CPS Pre-History at DARPA (1997-1999+)

- **Software Enabled Control (SEC)**
  - ***Q: How to reconcile physical system control formulations (e.g., continuous, closed-form control) with discrete event and state-transition behavioral formulations from computer science?*** Hybrid automata, hybrid/multi-modal control, Open Control Platform.
  - Conclusion: Two-week flight test program at Edwards AFB, transitioned to Boeing platforms.
- **Program Composition for Embedded Systems (PCES)**
  - ***Q: How to better instrument embedded software (e.g., for timing/resource management, memory isolation, concurrency, monitoring) so as to improve localization and granularity?*** (Hindley-Milner/LCF parametric types, model checking)
  - (Later, a related direction) Distributed Object Computing, C++ type-based, embedded software.
- **Model Based Integration of Embedded Software (MoBIES)**
  - ***Q: How to use model-based guidance and process-based software components for formally integrating embedded systems software?*** Ptolemy, MathWorks.
- **QoS Resource Mgmt for Open Distributed Realtime Systems (Quorum)**
  - ***Q: How to manage computing and communication resources for distributed real-time embedded systems?*** ACE+TAO, distributed real-time middleware, RealTime CORBA, flight tested as part of joint DARPA/AFRL Weapon System Open Architecture program

CPS Pre-History at NSF (2000-2005) - *Bootstrapping*

- **NSF institutional logistics and CPS program formation**
  - **Embedded and Hybrid Systems** (CPS precursor created in the CCR Division) – traditional NSF small program, budget augmented by topics, funding from the NSF-wide Information Technology Research (ITR) program.
- **Enabling events leading to CPS program**
  - OSTP NITRD High Confidence Software and Systems(HCSS) interagency coordinating group with NSF, NIST, FDA (CDSR), NIH, NASA, NSA, DOT, DOD formed to provide Federal budget coordination (and more…!) (**Frankie King**-NITRD HCSS Technical Coordinator)
  - Workshop series covering multiple domains (Automotive, Medical Devices, Aviation, Energy) …augmented by other agency- and university-led workshops including substantial industry participation.
- **PCAST** report prioritizes *Network and Information Technology (NIT) Systems* ***Connected with the Physical World****, software, and digital data*
- **External technical coordination**
  - ACM SIGBED, IEEE TCRTS
  - Supportive CPS research community rallies including “Three Musketeers”

Creating a CPS Program Inside NSF

- **Non-traditional but key elements of the program**
  - Cross-directorate collaboration (CISE, ENG directorates), interagency collaboration
  - Annual PI Meetings to foster and support an emerging CPS community
  - CPS virtual organization" with infrastructure for sustained community interaction, communication, artifact preservation/curation/storage

- **Building a CPS-ready workforce**
  - National Academies study towards CPS-ready workforce, *(funded 2012)*
    "A 21st Century Cyber-Physical Systems Education"
  - Jack Stankovic, co-chair National Research Council's Computer Science Telecommunications Board (CSTB)
  - Introducing CPS into Computer Science and Engineering curricula
  - Spontaneous instantiation by multiple universities

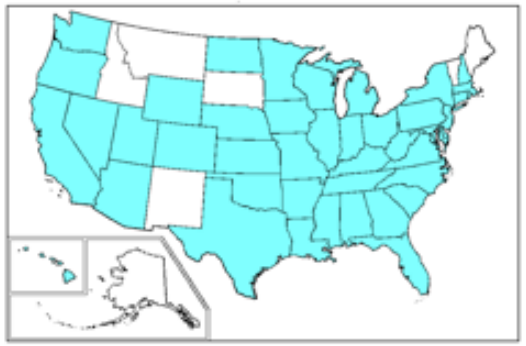
Key Developments

- **2006** –Key activities
  - **Wei Zhao**, ("then a miracle happened") CNS Division Director: **"Bring a 2-pager", …but "Cyber-Physical Systems**
  - NSF-sponsored planning industry/academia workshop, "imagining" CPS Academia/Industry (Al Mok, UT Austin)
- **2008** - First CPS Week conference led by Wash U (HSCC, RTAS, SenSys, ICCPS), St. Louis
  - Jeannette Wing, CISE AD keynote on CPS
  - NSF, Cyber-Physical Systems Summit, April 24-25
- **2008** July- Don Winter (Boeing VP, Phantom Works) congressional testimony (S&T, NITRD) advocating importance of CPS and need for industry-academia collaboration
- **2008** December 15 - Cyber-Physical Systems Information Day (program announcement)
- **2010** - PCAST calls for investment in CPS research because of its scientific and technological importance as well as its potential impact on grand challenges in a number of sectors critical to U.S. security and competitiveness

If You Build It, Will They Come?

FY 2009, by the numbers:

- 642 Proposals, totaling $580M in requests
- 527 CPS Projects, $45M in awards ($15.8M ARRA)
  - 248 Small → 30 funded (~12%)
  - 249 Medium → 26 funded (~10%)
  - 29 Large → 2 funded (~7%)





ARRA - American Recovery and Reinvestment Act

CPS Trajectory, as of Oct 2013

- Approximately 250 awards in 5 years
  - Mostly team projects
  - Many multi-university projects
- Extremely competitive program
- Improving portfolio balance:
  - Fewer "projects" (one-off solutions)
  - Increase in core scientific contribution
  - Principled technology efforts
- Thriving international community, professional societies (*leadership matters!*)

DARPA ITO

Shankar Sastry, David Tennenhouse
PMs: Helen Gill (SEC, PCES), Janos Sztipanovits (MOBIES), Gary Koob (QUORUM) , Doug Schmidt, John Bay
AFRL : Ray Bortner, Bill Koenig
NSF CISE AD: Ruzena Bajcsy

CPS origin at NSF, 2008

Wei Zhao, CNS DD
Ty Znati, Bob Trew
Jeannette Wing, **Tom Peterson**, CISE & ENG partnership
PDs, IPAs and Experts: Helen Gill**,** Kishan Baheti, Scott Midkiff, Bruce Krogh, Michael Branicky, …

Interagency: Frankie King (NCO), Al Wavering (NIST), Brad Martin (NSA), AFRL, NASA, DOT, FDA, NIH, DOD

CPS, 2013

Farnam Jahanian, CISE AD
Keith Marzullo, CNS and CPS Senior Steering Group
Helen Gill PD (retiring)
David Corman PD (incoming)
The entire CISE-ENG PD team (Ted Baker, Ralph Wachter, Sylvia Spengler, …)
Vijay Kumar - OSTP
The HCSS/CPS agencies in NITRD

Then: A 2013 Checkpoint, Looking to 2014

- **Beyond motion planning**: design for certifiably dependable control of (complex, multi-physics) systems
- **Interdependency** of questions from control, real-time systems, safety, security (certainly a platform question – but also an interdisciplinary systems science issue)
- **Next generation system, software, and control architectures**, dynamically orchestrated behaviors -- “What’s in a mode?” (design for cooperation/coordination/receptiveness; is the safety controller reachable?)
- **Next generation system ID** (bridging machine learning with traditional system ID state estimation, stochastics and uncertainty, purpose/usage context: reactive and predictive control)
- **Real-time Cloud, “Industrial Internet”** connecting CPS at distance; whither quality of service?

Horizons receding, what challenges stay the same?

- Interplay : science, mathematics, fundamental questions; engineering; transition; use.
- Safety: Cyber-Physical Systems carry an assurance burden, spanning design, development, and operation.
- Context: Offline theory vs. online reality – resource management in real time, platform variety, emergent failures, complex environments.
- Complexity: Disciplined abstraction (E.g., from digital twins to stable, reliable interfaces and analyses). Mixed-authority, mixed-criticality, reconfigurable, supervisory control
- Composition: Reconfigurable, composite systems require agile, principled composition and evaluation methods.

  We used to think that if we knew one, we knew two, because one and one are two.

  We are finding that we must learn a great deal more about "and." ***(Sir Arthur Eddington}***

- Reality: Neither a smooth function nor a rear-view mirror, "stuff happens."

  "Another beautiful theory, murdered by a gang of facts." (Search, but verify!)

What happened since then

- CPS CAREER Proposals since 2013. More than 100 CAREER awards by CNS since. Additional “related” CAREER funded by CISE and ENG.
  - Four PECASE awardees from CISE in CPS since 2013 plus additional from CISE and ENG
- CPS PI meetings from 2010 – 2025 with typical attendance of around 500 – more than many conferences
- CPS has been a tough program with awards sometimes falling into single digits. Growing community through multiple Aspiring PI meetings, and Rising Stars for Early Career researchers
  - Provide resources to CPS community with program artifacts – virtually every project has poster on the VO
  - CPS-VO started 2009 – a steal @ 200,000 / year for five years. Supports multiple programs and agencies
- CPS Frontier awards and transition to practice awards

Frontiers Span Multiple Research Spaces

- **Incentives and Resilience** – Foundations of Resilient CybEr-Physical Systems (FORCES)
- **Control** - *Correct-by-Design Control Software Synthesis for Highly Dynamic Systems*, and, *Computation-Aware Algorithmic Design for Cyber-Physical Systems*,
- **Time** - ROSELINE: Enabling Robust, Secure and Efficient Knowledge of Time Across the System Stack
- **Biology** - BioCPS for Engineering Living Cells
- **CPS Resilience** - CHORUS: Resilient Distributed CPS through Rational and Dynamic Decision-Making Among Multiple Stakeholders
- **Manufacturing** - Data-Driven Cyber-physical Systems, Software Defined Control for Smart Manufacturing Systems
- **Medical** - *Compositional, Approximate, and Quantitative Reasoning for Medical Cyber-Physical Systems*, and, *Bi-Directional Brain-Computer Interface for Restoration of Walking and Lower Extremity Sensation after Spinal Cord Injury*
- **Autonomy** - *Cognitive Autonomy for Human CPS: Turning Novices into Experts*, and, *VeHICaL: Verified Human Interfaces, Control, and Learning for Semi-Autonomous Systems*
- **Smart Cities** - SONYC: A Cyber-Physical System for Monitoring, Analysis and Mitigation of Urban Noise Pollution
- **Agriculture** - COALESCE: COntext Aware LEarning for Sustainable CybEr-Agricultural Systems
- **Space** - Software-Defined Nanosatellite Constellations: The Foundation of Future Space-Based Cyber-physical Systems

CPS Partnerships – Model for Interagency Collaboration

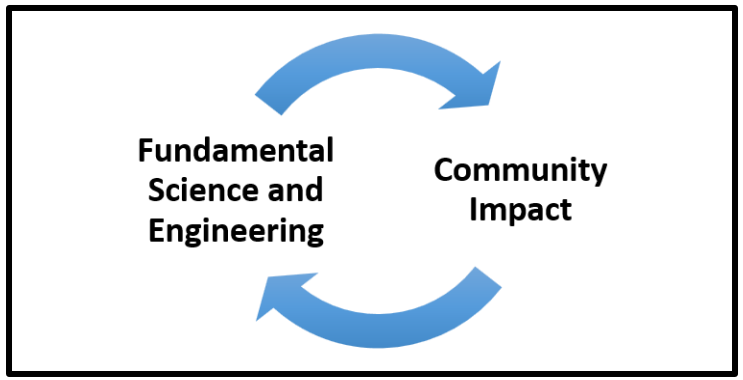
- Many commenced as a result of NITRD CPS and HCSS working groups leading to joint solicitation
  - DHS, DOT/FHWA, NASA, NIFA, NIH
- NSF/Intel Partnership on Cyber-Physical Systems Security and Privacy (CPS-Security) – 2015 leading to several transition to practice
- International partnerships with JST and DFG (Germany) and many external discussions with EU, Singapore, and others

CPS Research Impacts at NSF -- Over $1B

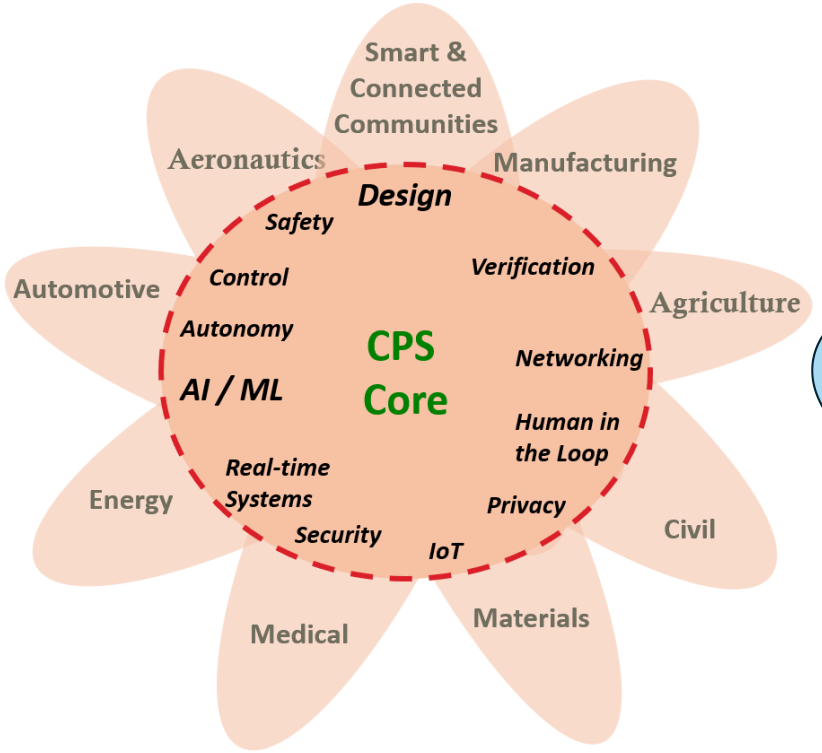
- Over $900M in CPS awards with over 250 unique institutions and more than 6000 students directly supported
- CPS foundation for additional programs Smart and Autonomous Systems and Safe Learning Enabled Systems – what does safety mean in the context of autonomous systems
- CPS VO
  - Create a community and provide program artifacts from program origination
  - Resource for new researchers, federal agencies, industry, and anyone looking to see what the state of the art is

Smart and Connected Communities and CIVIC

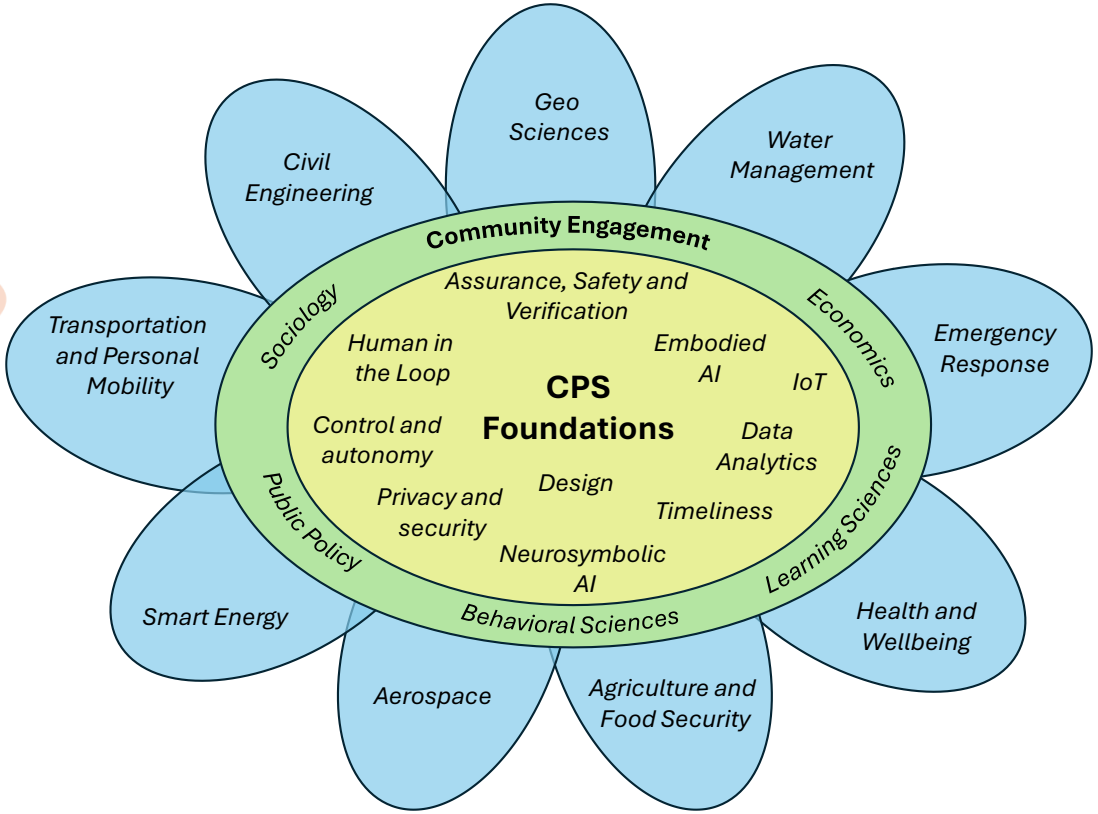
- CPS was the seed for new programs Smart and Connected Communities and CIVIC Innovation Challenge
  - S&CC:10-15-year horizon
  - CIVIC: 1 – 5-year horizon (similar to TTP)
- Focus - How do we ensure that fundamental science **improves quality of life** in communities in both the short- and long-term
- Key importance of technology – but also fundamental perspectives on people and communities – sociotechnical research
- Cross-directorate and inter-agency
- Program awards exceeding $300M with 200+ institutions and spawned partnerships with DHS, DOE, FEMA, NIFA, and Department of State (Southeast Asia)



CPS Related Programs and Flower Diagram



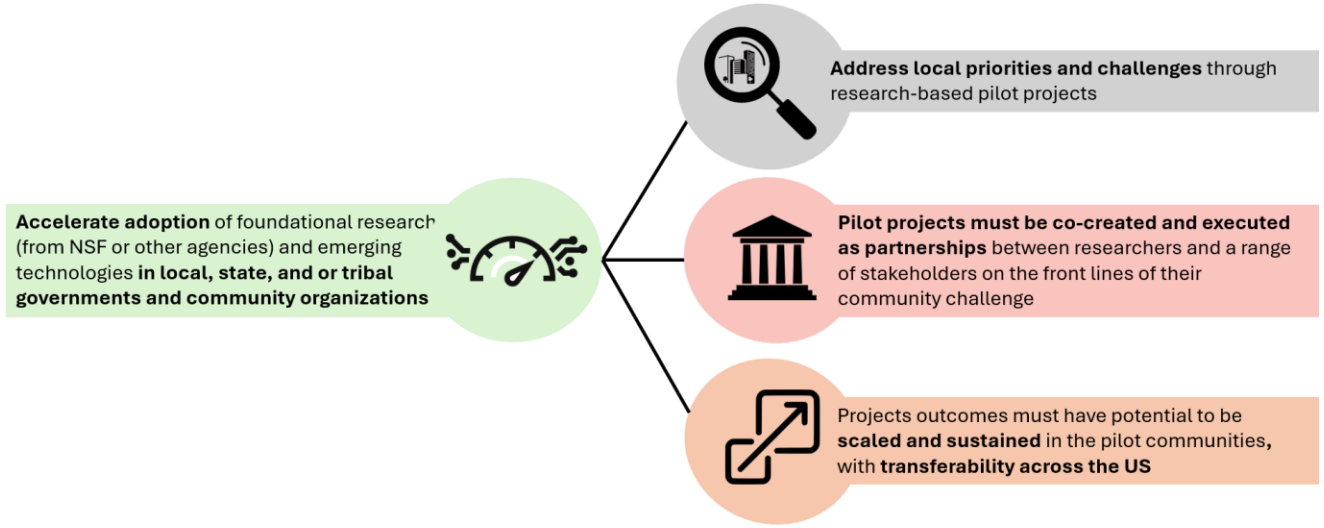
CPS Flower Diagram – Circa 2018

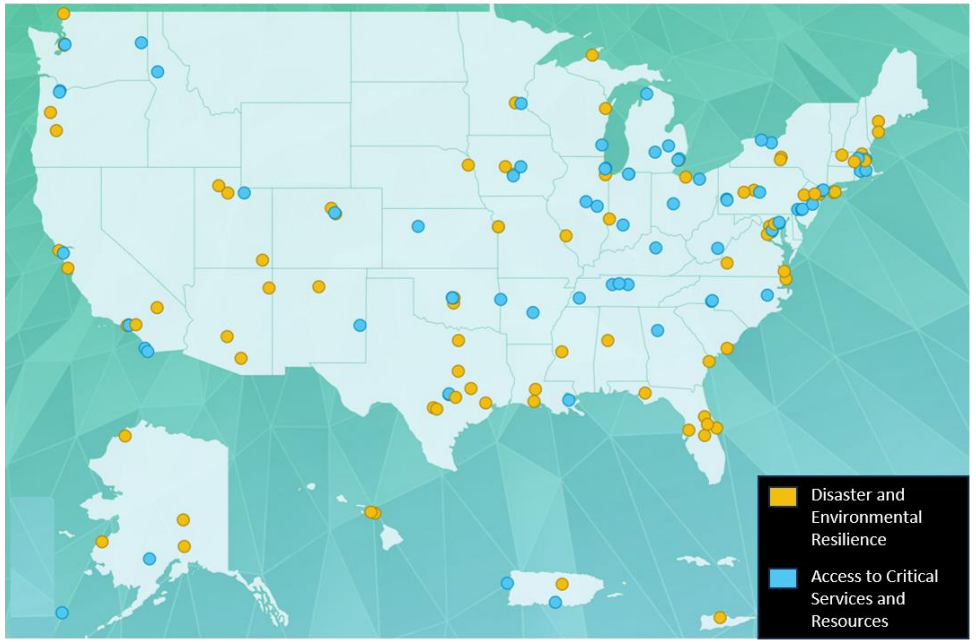


CPS / S&CC Flower Diagram – Circa 2025

A fundamental understanding of the complex, dynamic interactions between technology and society is essential for unlocking the potential benefits of smart and connected communities.

CIVIC Research and Action Impacts Support Resilience and Access to Critical Services





CIVIC 1.0 (2020-2022)

- Launched as a partnership between NSF, DOE, and DHS /FEMA.
- CISE and ENG funding
- 52 Stage 1 Planning Awards
- 17 Stage 2 Pilots

CIVIC 2.0 (2022-2024)

- USDA/NIFA joins as new federal co-funder
- Additional partners in SBE and GEO
- 56 Stage 1 Planning Awards
- 22 Stage 2 Pilots

CIVIC 3.0 (2024-2026)

- Additional funding from BIO
- 52 Stage 1 Planning Awards (funding from CISE, ENG, SBE, GEO, and BIO)
- 14 Stage 2 awards funded

What has the CPS Program Meant

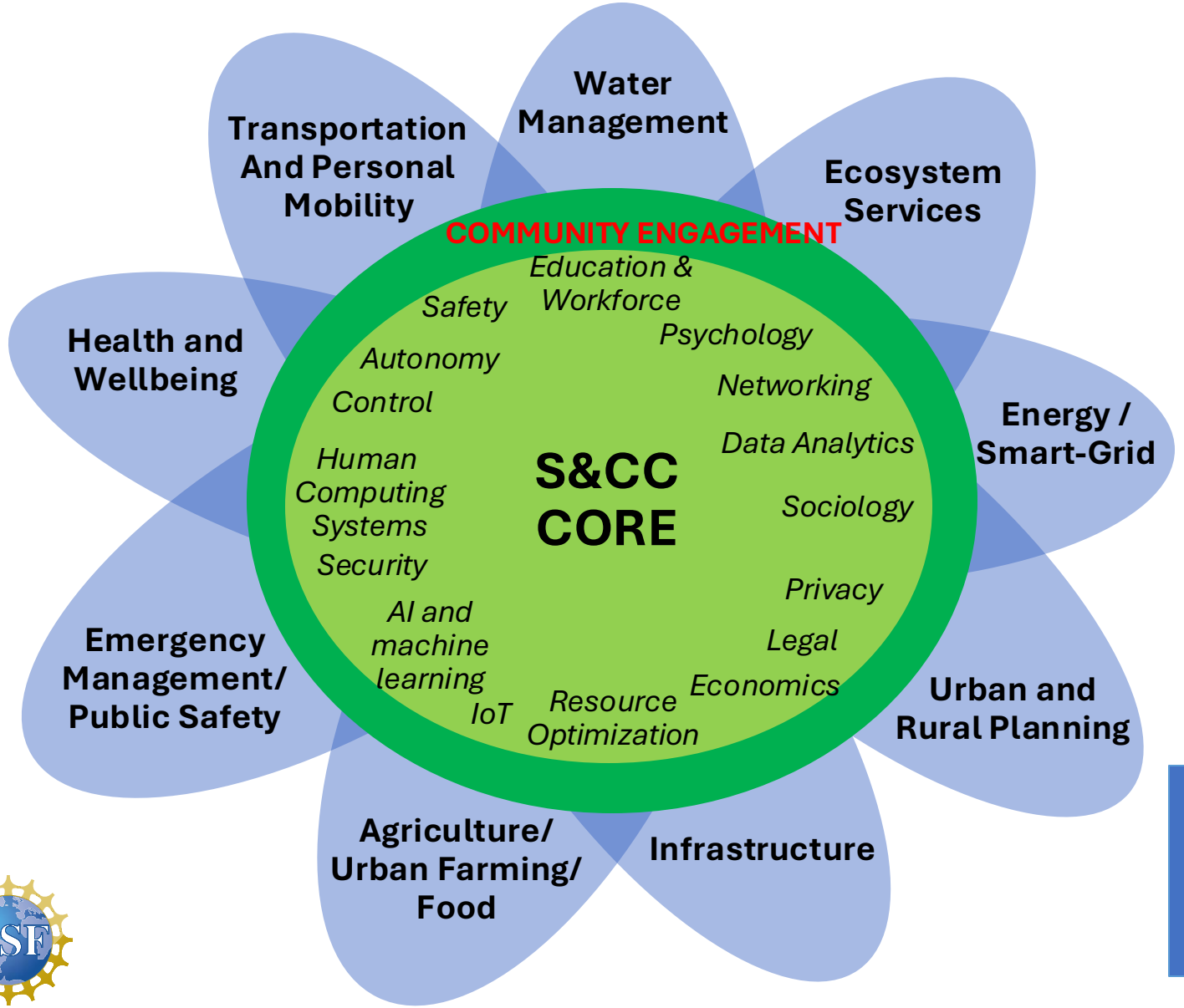
- **Created** a new way of thinking that moved beyond conventional embedded systems toward systems combining computation, sensing, networking, control, and physical processes.
- **Created reusable scientific foundations across many industries.** CPS developed cross-cutting techniques for **control, real-time systems, networking, machine learning, autonomy, safety, security, privacy, and formal verification**. Those techniques can be applied to transportation, energy, manufacturing, healthcare, agriculture, and infrastructure.
- Developing methods for **verification, security, privacy, safety, and resilience** of CPS.
- **Connecting** AI and Machine Learning into systems that have to operate safely in the real world.
- Producing **prototypes, tools, hardware/software, and testbeds** for real-world validation.
- **Spawned** new programs S&CC and CIVIC marrying technology and community engagement / social science to improve quality of life
- **Transitioning** technology and people into virtually every technology sector that we interact with today

But the world has changed since 2025!

- Nascent technologies are becoming emerging technologies with potential application in CPS
- Emerging technologies from the past have morphed and become both standard (e.g. machine learning) and potentially revolutionizing CPS (LLM and AI)
- CPS has moved into the CISE Core including foundational and community
  - **NSF 25-543: Computer and Information Science and Engineering : Future Computing Research (Future CoRe)**
  - *Cyber-Physical System Foundations and Connected Communities* (CPS) program;
- Inter-agency collaboration more challenging

Backup Material

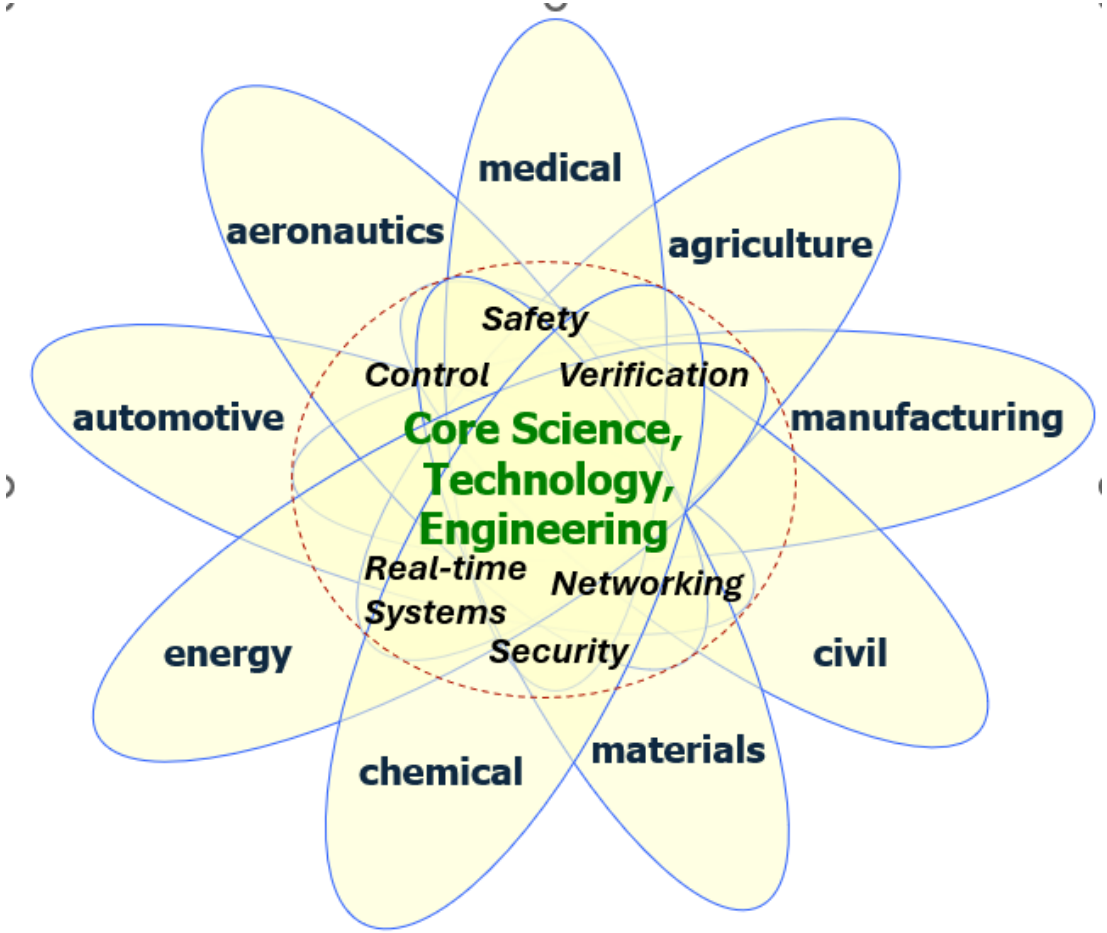
The value of fundamental research in smart and connected communities (S&CC)



A fundamental understanding of the complex, dynamic interactions between technology and society is essential for unlocking the potential benefits of smart and connected communities.

Enhances scientific and engineering knowledge in ways that improve the quality of life within communities.

Cyber-Physical Systems



Looking Backwards and Towards the Future