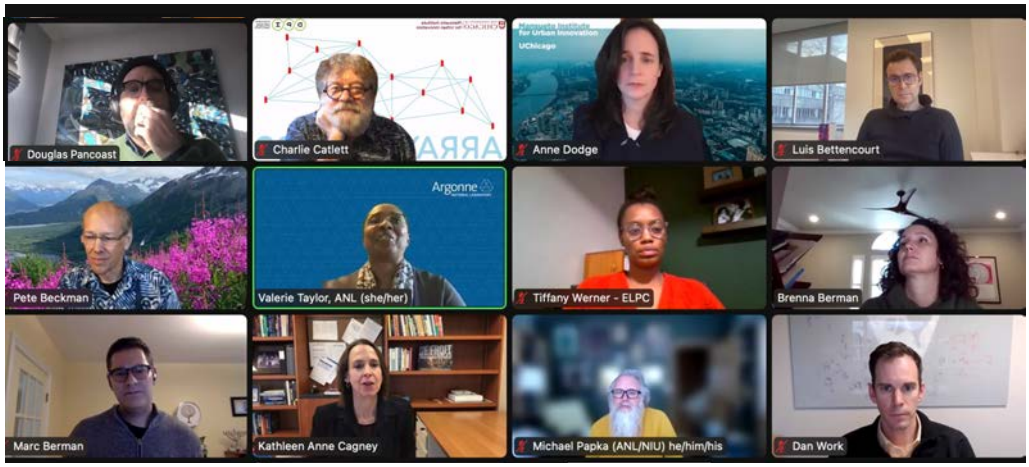

Some 120 participants from academia, government, industry, and community groups joined AoT leaders for the symposium.

In January 2012–exactly ten years ago—we began discussions with the City of Chicago regarding the possibility of installing scientific instruments as part of the City's Smart Lighting project (300,000 streetlights). On January 20th, 2022 the *Mansueto Institute for Urban Innovation* (Univ of Chicago) and the *Discovery Partners Institute* (Univ of Illinois System) hosted a discussion with AoT leaders about lessons learned and looking ahead at what we are building upon the Array of Things.

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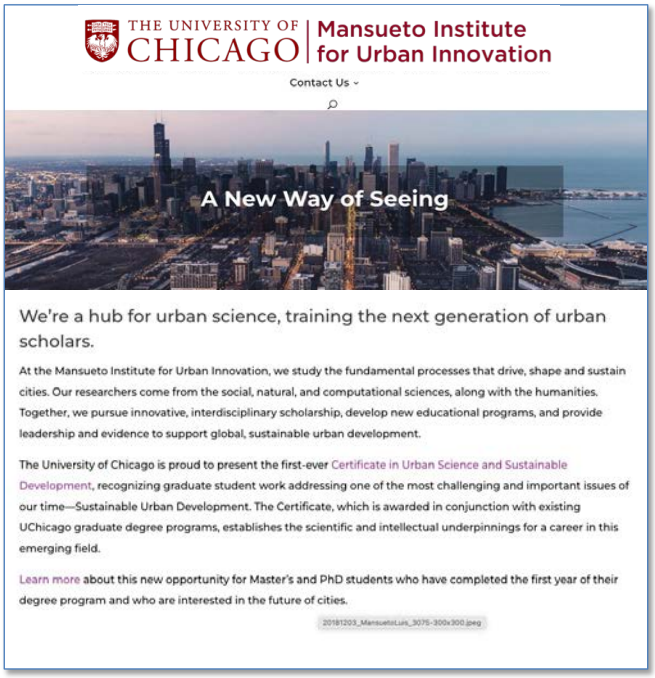

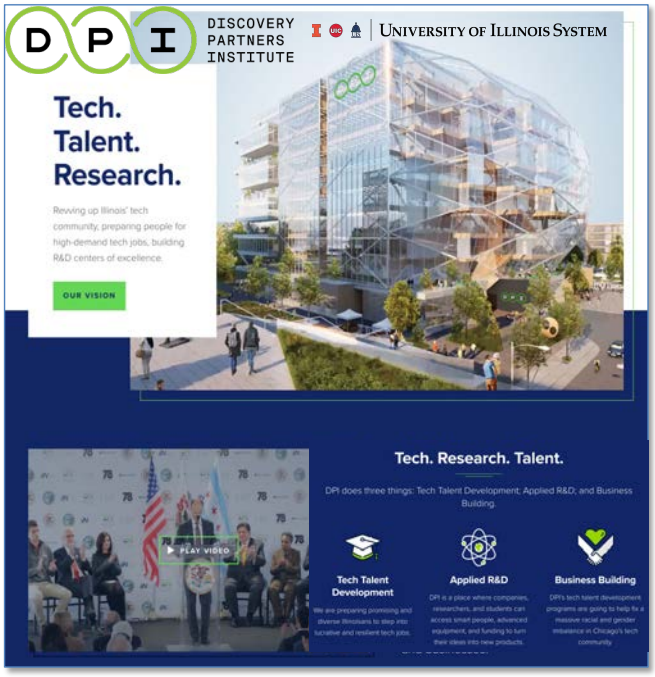

Today's Speakers

Charlie Catlett
DPI

Valerie Taylor
ANL/UChicago

Luis Bettencourt
UChicago

Anne Dodge
UChicago

INSIGHTS: LESSONS LEARNED

Kathleen Cagney
UMichigan

Michael Papka
ANL/NIU

Pete Beckman
ANL/Northwestern

Brenna Berman
Fmr City of Chicago

INSPIRATION: WHAT'S NEXT

Douglas Pancoast
SAIC

Tiffany Werner
ELPC

Daniel Work
Vanderbilt

Marc G. Berman
UChicago

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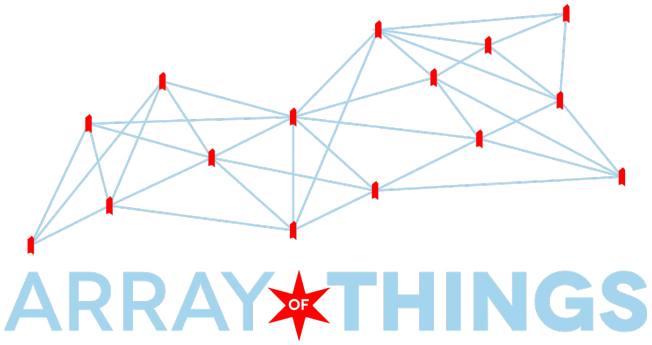
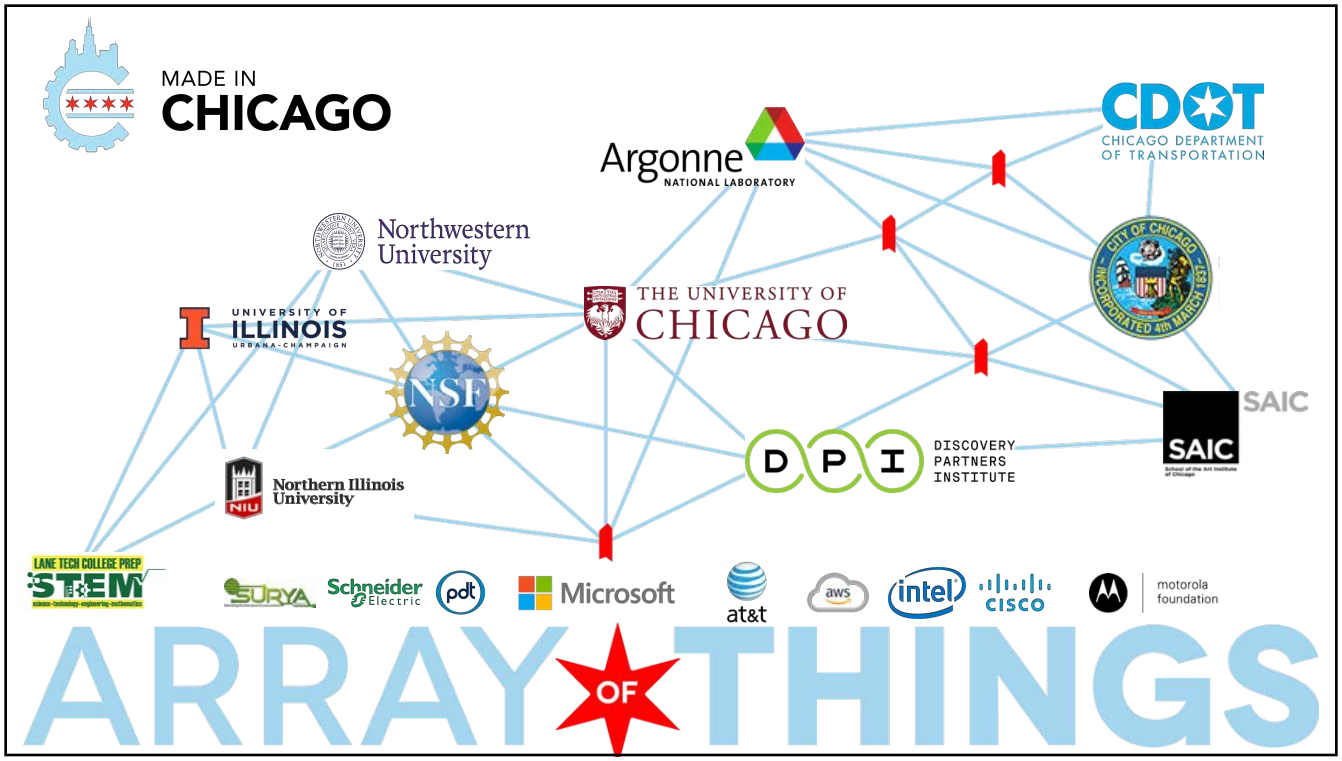


A Virtual Symposium
January 20, 2022

ARRAY OF THINGS



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What motivated AoT?

Origins, Design, and Launch

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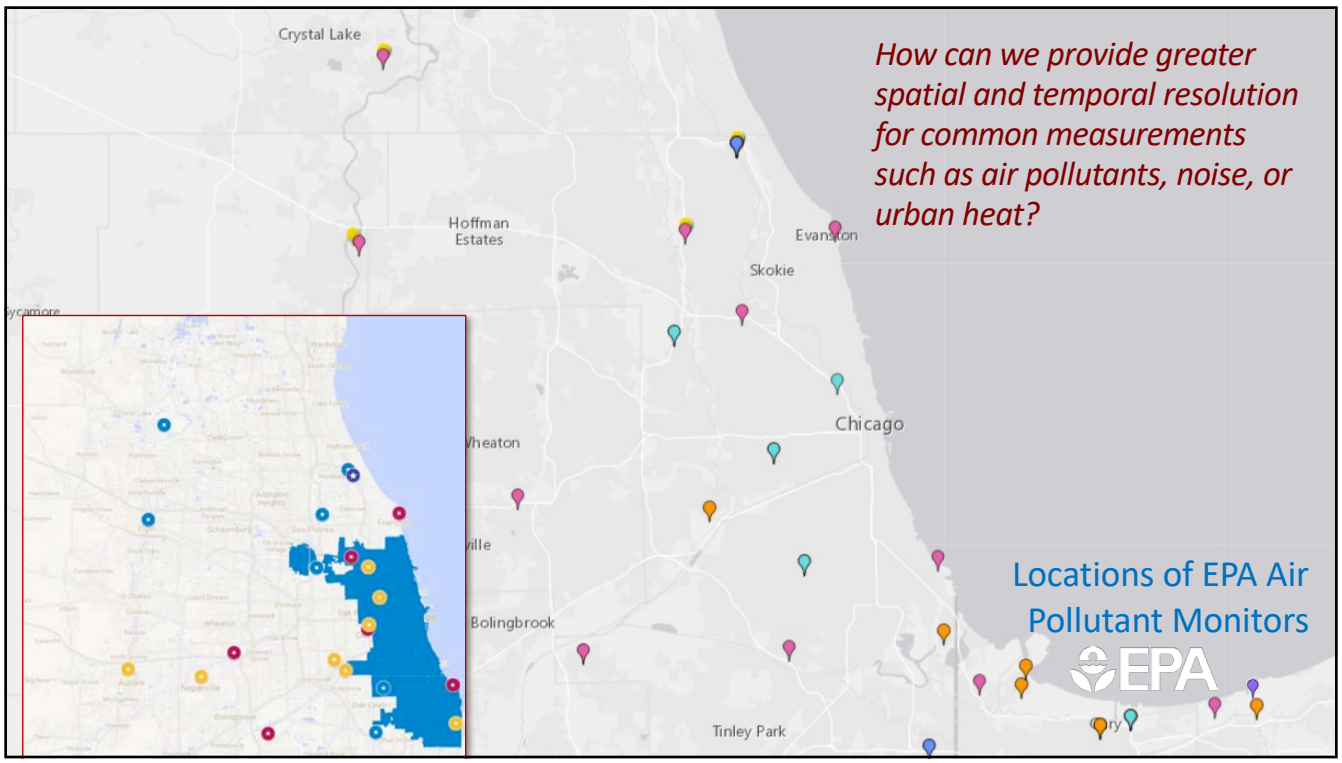

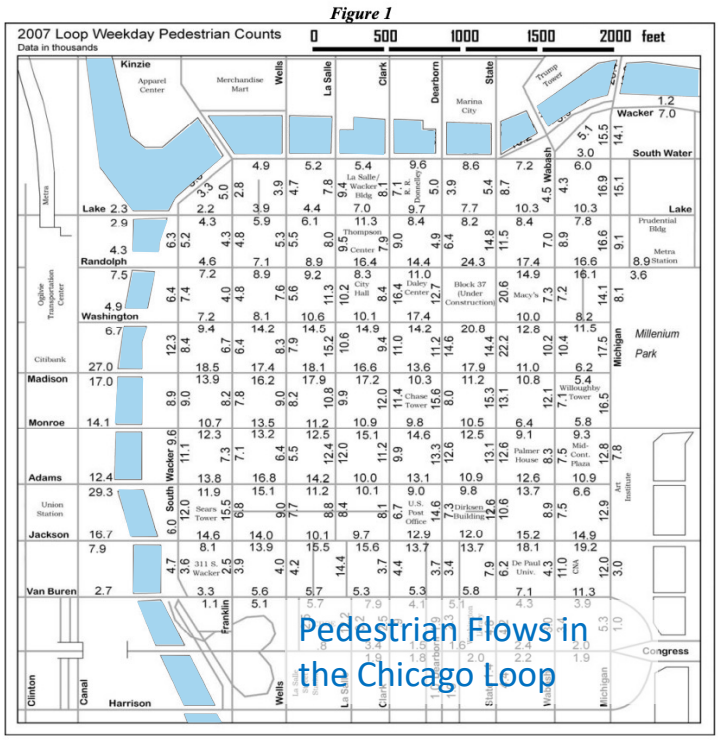

How can we use edge-AI to measure factors that traditionally require human observers, such as pedestrian flows, interactions among vehicles, or bicycle use?

Pedestrian Activity in Chicago's Downtown, prepared for Chicago Department of Transportation by TranSystems and TransInfo LLC, December 2008

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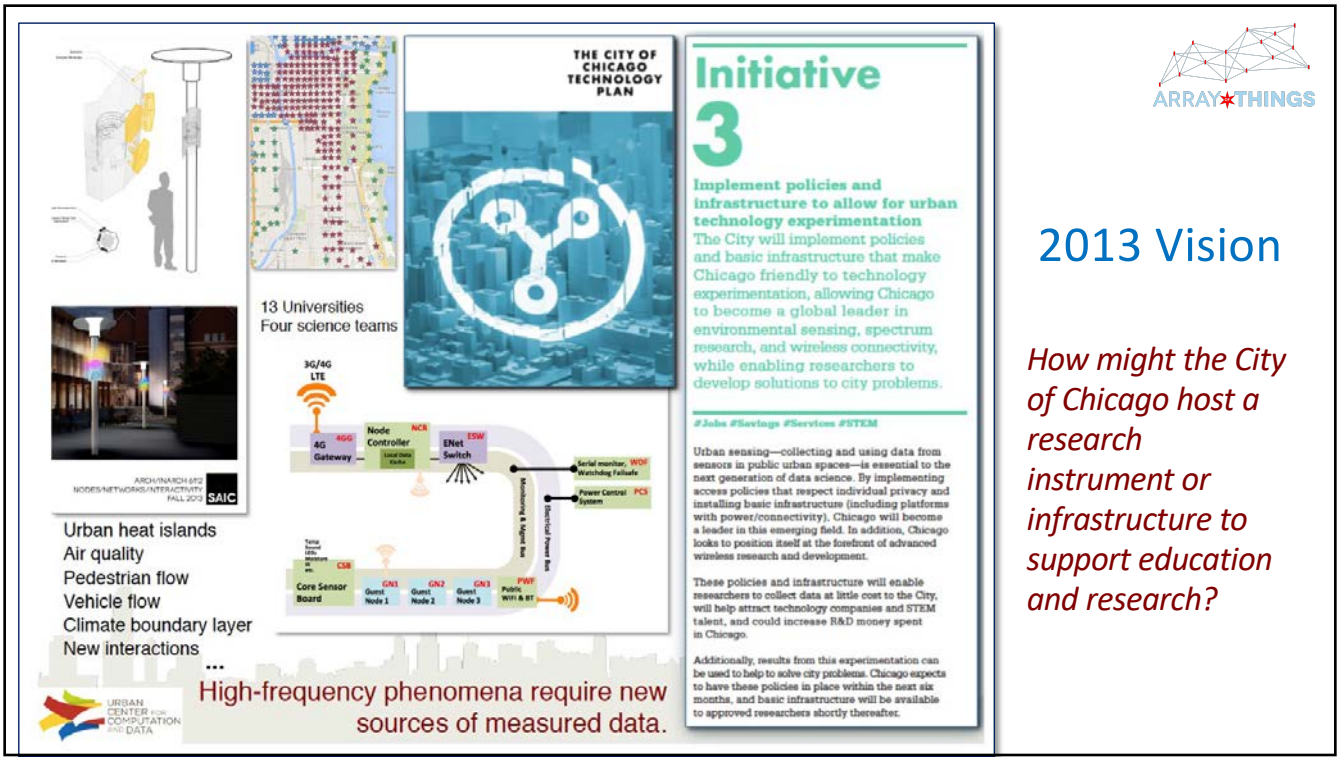

2013 Vision

How might the City of Chicago host a research instrument or infrastructure to support education and research?

AoT was a Science-Driven Instrument

SAGE "AI@Edge Science Workshop (April 2019 2017)

Workshop on Urban Scale Processes (May 2019)

Urban Landscape and Climate (August 2013)

Science Planning Workshop: An Urban Instrument for Measurement and Embedded Systems Research (January 2014)

Science Planning Workshop: MRI Proposal for Urban Measurement and Embedded Systems Research (October 2014)

Array of Things Partner Kickoff Workshop (September 2015)

Convening on Urban Data Science (April 2016)

Workshop on Urban Mobility in the Era of Smart and Connected Communities (February 2017)

Array of Things User Workshop (August 2018)

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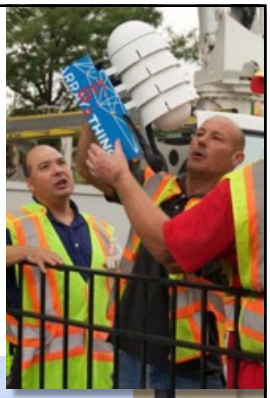
ARRAY OF THINGS

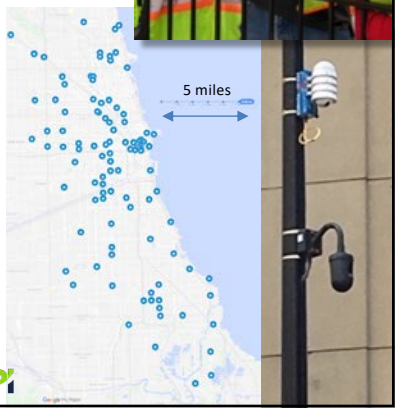
AoT Maximized Impact by driving the technology by urban research needs—not vice versa

Science input resulted in a design supporting traditional and experimental sensors, and *edge AI programmed measurements—requiring powerful computers in situ.*

Environmental and Air Quality Sensors

"Software-Defined Sensors"



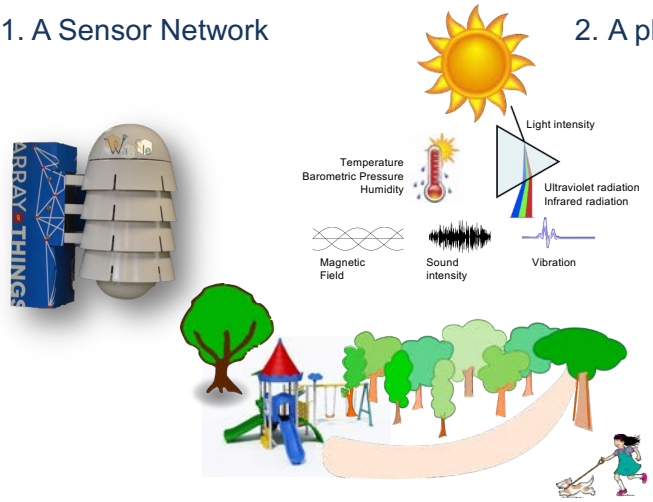


THE UNIVERSITY OF CHICAGO Northwestern University Argonne NATIONAL LABORATORY DPI

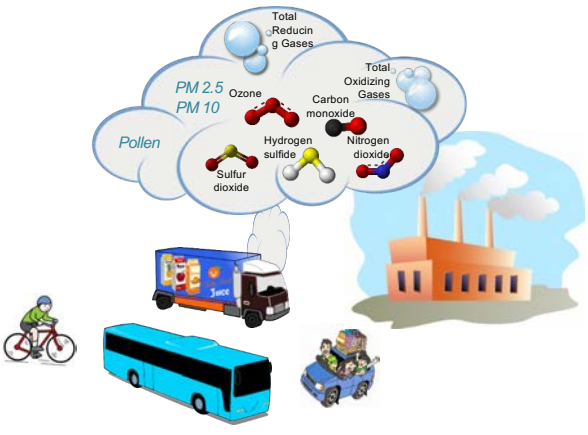
AoT: An Instrument with Three Functions

NSF

1. A Sensor Network



2. A platform to test new sensor technologies



3. A network of remotely programmable AI devices for R&D toward *perceptive infrastructure*

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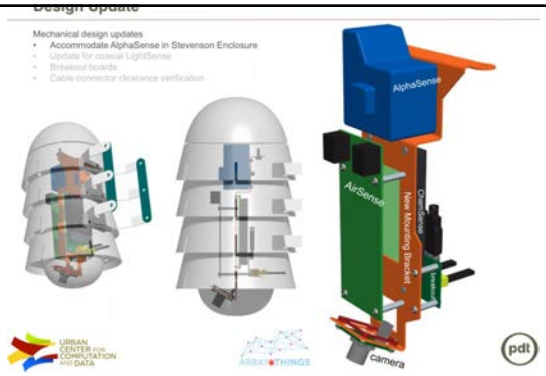
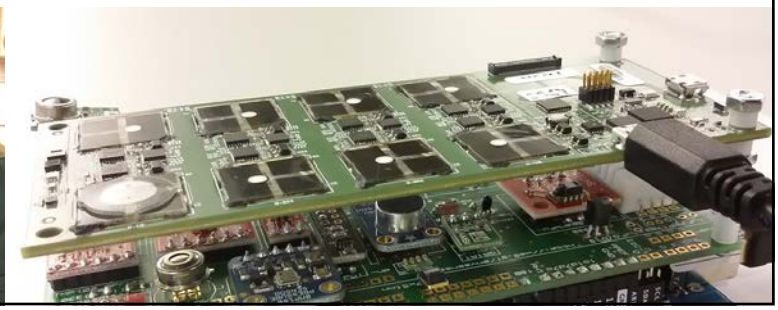
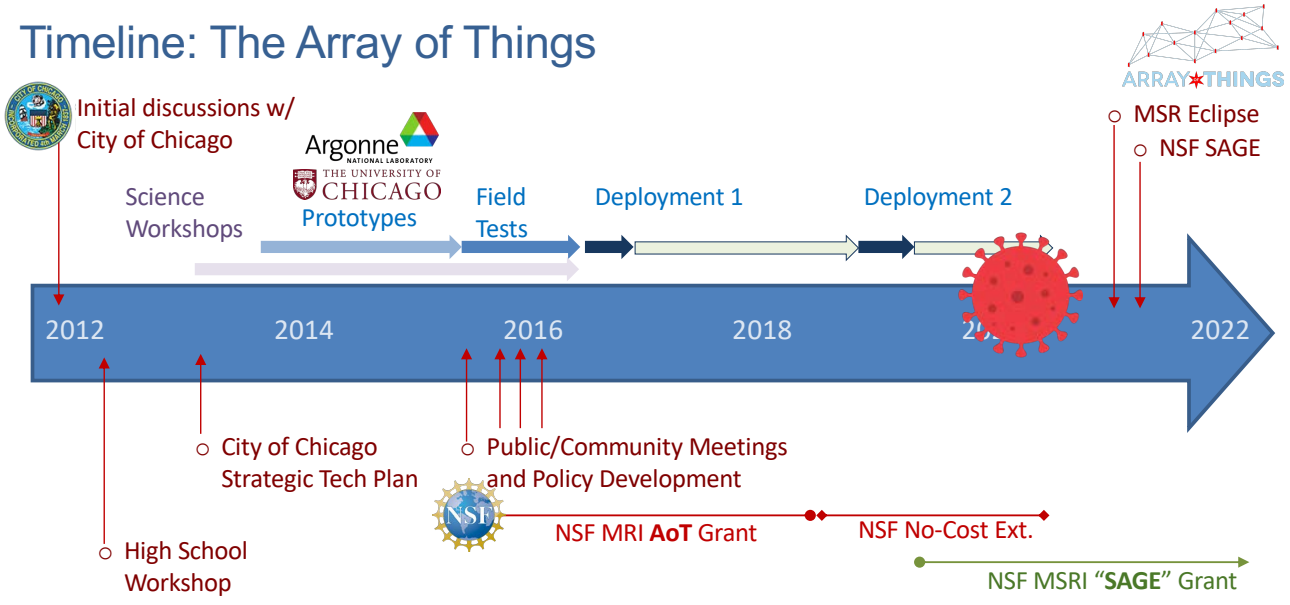


No open platforms existed to support these functions, so the team developed a new edge computing platform, *Waggle*.



Timeline: The Array of Things



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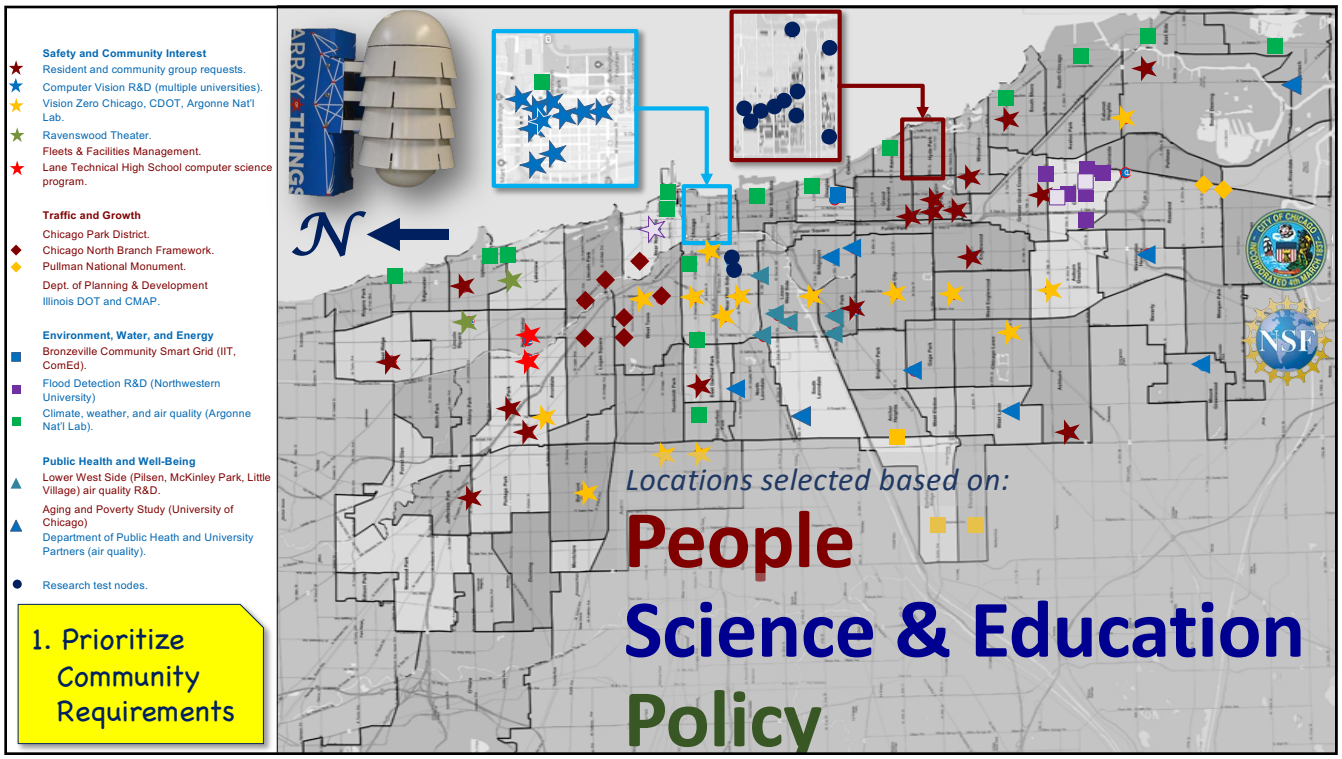
What have we learned?

Six key insights into translational research and the unique opportunities for *impactful* synergy among academics, city governments, and communities.



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ARRAY THINGS

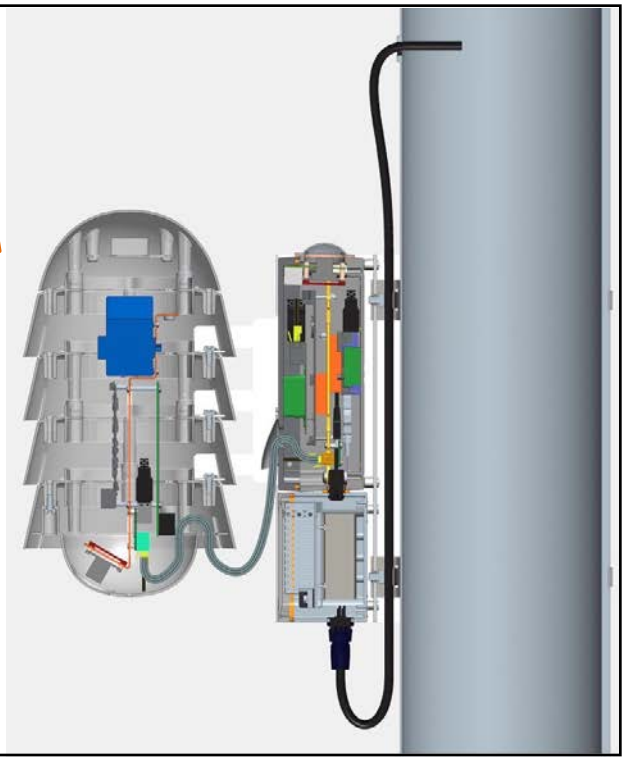
Argonne NATIONAL LABORATORY
Technology

Accountability
INDIANA UNIVERSITY
Center for Applied Cybersecurity Research

opengov FOUNDATION
Transparency

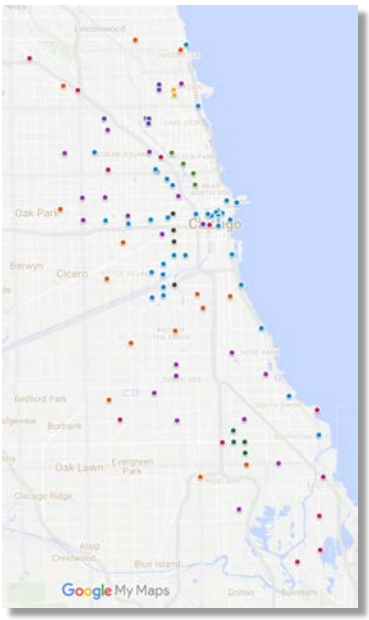
Privacy

2. Privacy built into the architecture

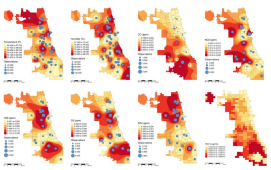


AoT: Open Data

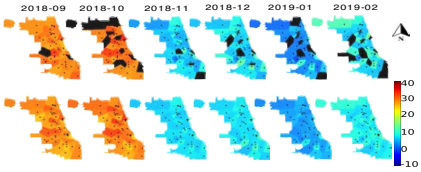
ARRAY THINGS



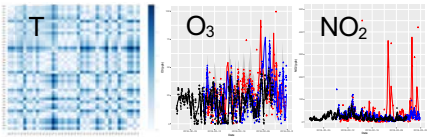
4,195,000,000 measurements



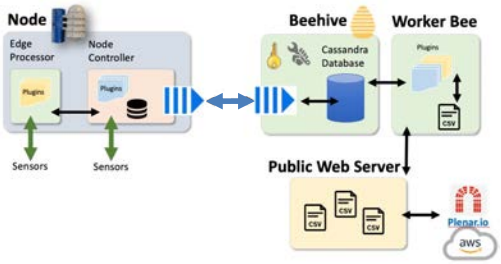
English, Zhao, Brown, Catlett & Cagney



Hu, Wang, Jiao, Sankaran, Catlett & Work



Potosnak, Sankaran, Papka, Kaberon, Kotamarthi & Catlett



Laha, Koschinsky, Kolak, Ladoy & Anselin

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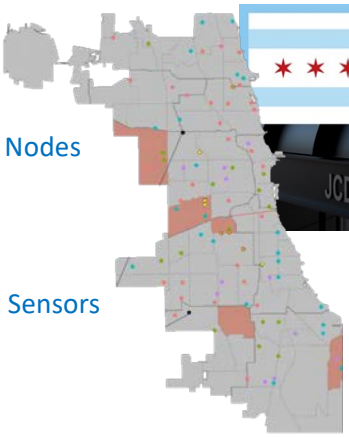
ARRAY THINGS

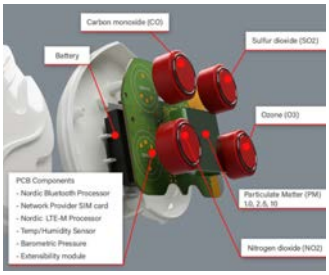
Community groups bring key perspectives and expertise.

~50-100 Edge-AI Nodes

+

~100s of Low-Cost Sensors





3. Engage Community Expertise

4. Make data *legible*

CDOT CHICAGO DEPARTMENT OF TRANSPORTATION · Microsoft · DPI · ENVIRONMENTAL LAW & POLICY CENTER · JCDecaux

5. Engage Youth

"Lane of Things," funded by the Motorola Foundation with leaders at Lane Tech (Jeff Solin, Dan Law), the School of the Art Institute of Chicago (Douglas Pancoast, Satya Basu, and Robb Drinkwater), and UChicago (Kate Kusiak Galvin, Charlie Catlett)

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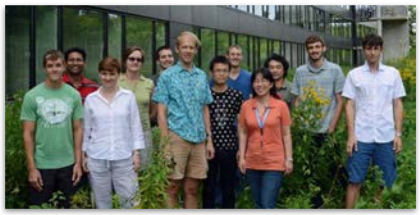
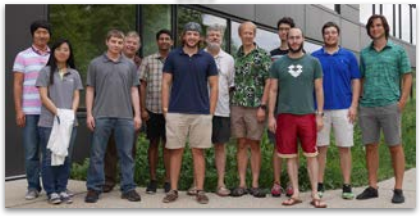
ARRAY THINGS



2013

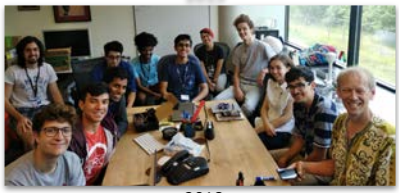
2014

2015

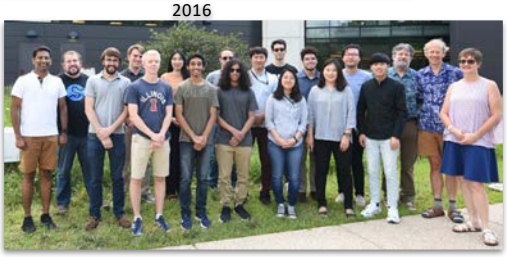


2016

2017



2018



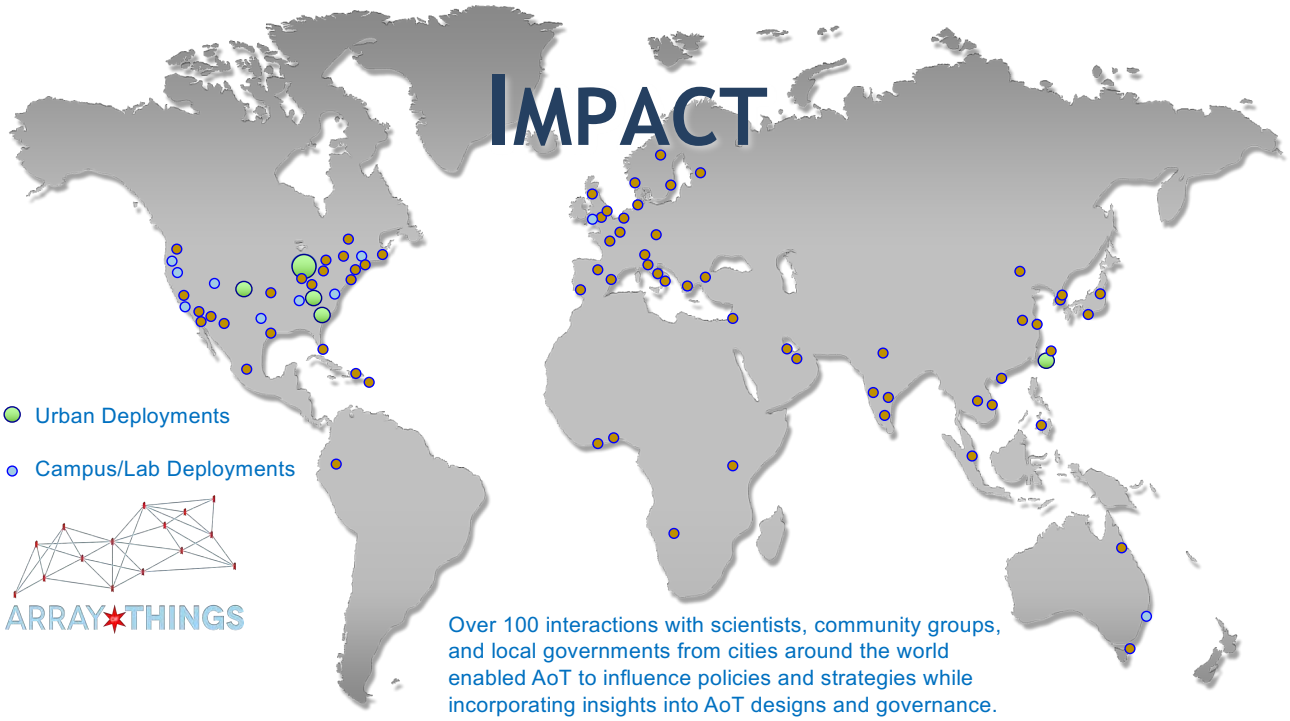
2019

2020

2021

Summer students are funded through the DOE SULI program as well as AoT, SAGE, and other grants.

IMPACT



ARRAY THINGS

Over 100 interactions with scientists, community groups, and local governments from cities around the world enabled AoT to influence policies and strategies while incorporating insights into AoT designs and governance.

AoT Science Exemplars

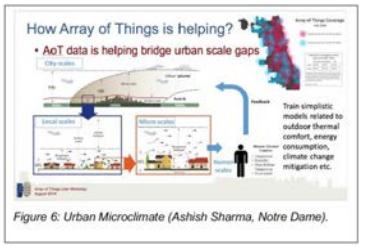


Figure 6: Urban Microclimate (Ashish Sharma, Notre Dame).

Figure 7: Behavioral Sciences (Marc Berman, UChicago).

Figure 8: Computer Science (Nicola Ferrier, ANL/UChicago).

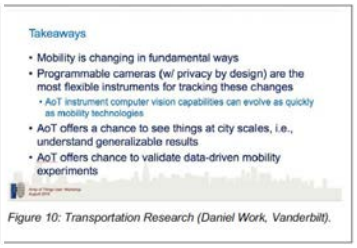


Figure 10: Transportation Research (Daniel Work, Vanderbilt).

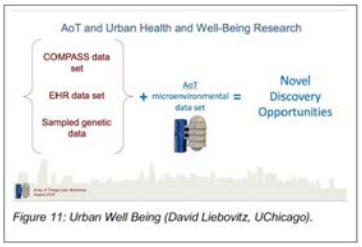


Figure 11: Urban Well Being (David Liebovitz, UChicago).

Figure 9: Social Sciences (Kathleen Cagney, UChicago).

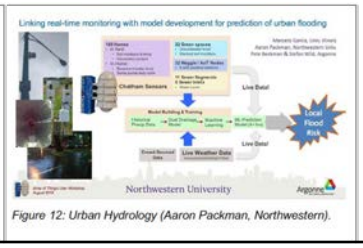


Figure 12: Urban Hydrology (Aaron Packman, Northwestern).

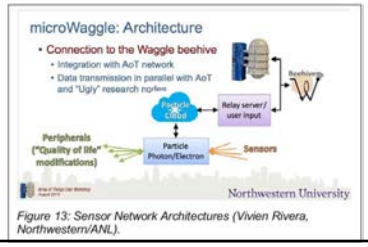


Figure 13: Sensor Network Architectures (Vivien Rivera, Northwestern/ANL).

Example Papers and Articles

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Where are we going now?

"AoT 2.0"

- Increased AI@Edge capabilities and decreased barriers to entry.
- Dozens to hundreds of devices in selected locations-of-interest.
- Increased density and decreased cost for key urban measurements.
- Hundreds to thousands of devices for comprehensive coverage.

Sage

A Software-Defined Sensor Network

Cyberinfrastructure for Edge Computing

www.sagecontinuum.org

SAGE: National Cyberinfrastructure for Distributed Sensing: Moving Artificial Intelligence to the Edge

Pete Beckman, Eugene Kelly, Charlie Catlett, Ilkay Altintas, Scott Collis, Nicola Ferrier, Raj Sankaran, Jim Olds, Valerie Taylor, Dan Reed, Frank Vernon, Joe Swantek, Mike Papka, Bill Miller, Aaron Packman, Irene Qualters, and many more…

Northwestern University · The University of Chicago · Northern Illinois University · Argonne National Laboratory · Colorado State University · UC San Diego · George Mason University · DPI Discovery Partners Institute · Array of Things · ARM · NEON National Ecological Observatory Network · HPWREN SDSC San Diego Supercomputer Center · Lincoln Park Zoo For Wildlife. For All. · OHAZ

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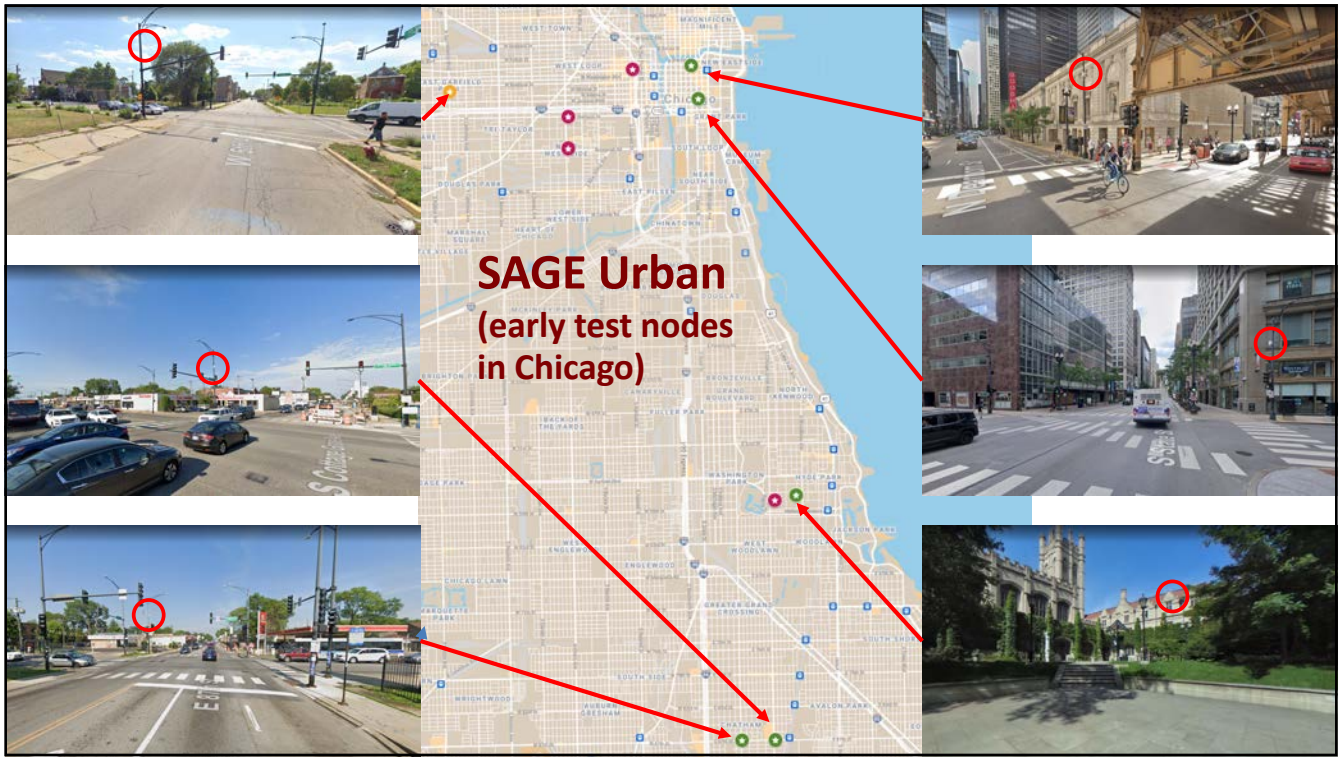
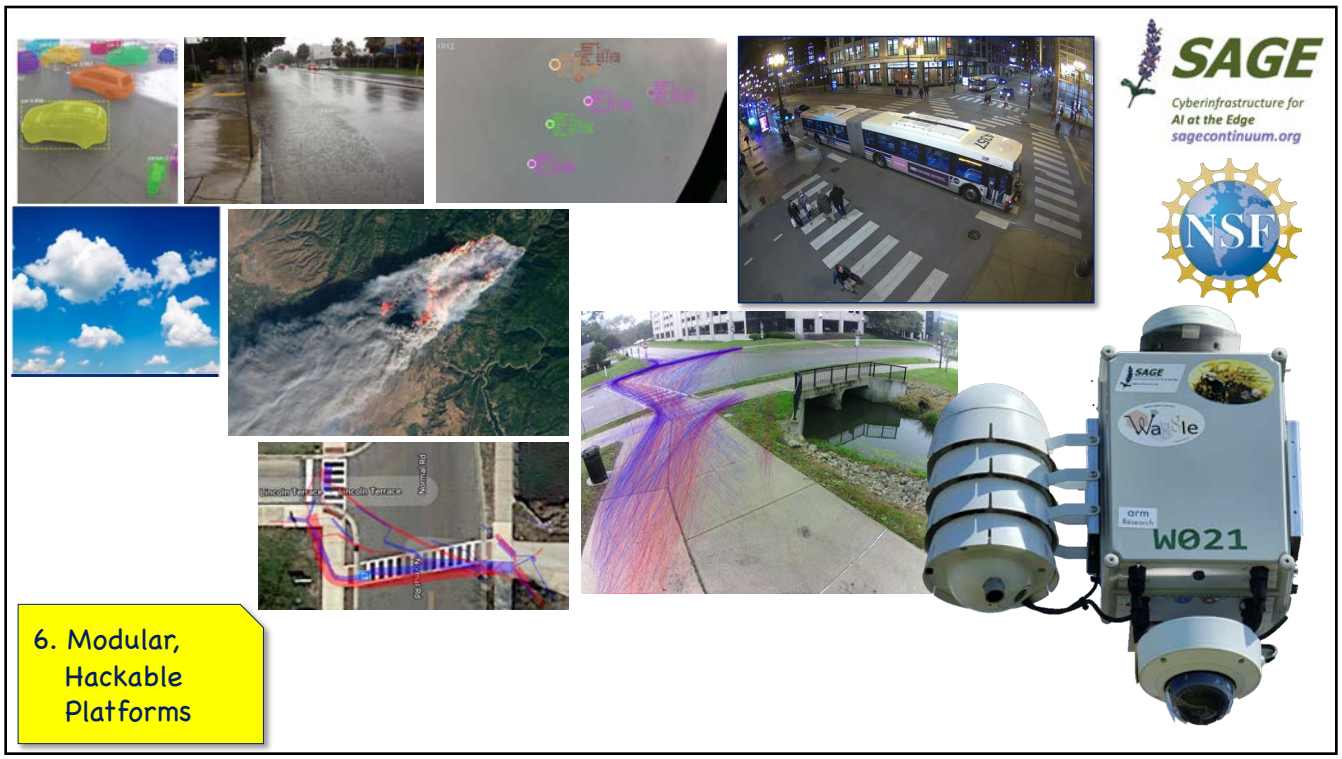
ARRAY OF THINGS





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Insights: Lessons Learned

Valerie Taylor (ANL/UChicago) (Moderator)
Pete Beckman (ANL/Northwestern)*
Kathleen Cagney (UMichigan)*
Brenna Berman (Former CIO, City of Chicago)
Michael Papka (ANL/NIU)*

*Array of Things NSF grant Co-Principal Investigator

Pete Beckman

Distinguished Fellow at Argonne National Laboratory and the Co-Director of the Northwestern University / Argonne Institute for Science and Engineering. As Co-Principal Investigator of AoT, Pete was the architect of the Waggle platform, first deployed in AoT and today forming the basis for the SAGE project.

ARRAY THINGS

AI @ Edge

Sensors


LIDAR

Software Defined Radios


Hyperspectral Imaging

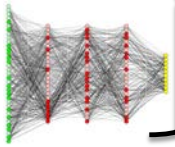
Facilities

Actuators


Servos


Dynamic adaptation

Powerful
Parallel Edge Computing



Artificial Intelligence
Deep Learning Inference
Lightweight Training

Edge computing and deep learning with feedback for continuous improvement

5G ESnet

Reduced, Compressed data

New inference (model)
Adaptive steering

HPC

Deep Learning Training
Simulation / Forecast

Why Live on the Edge?

- **More data than bandwidth**
  - Spallation neutron source, light source, SW defined radios, HD Cameras, LIDAR, radar, hyperspectral imaging, grid micro-synchrophasors, etc.
- **Latency is important**
  - Quick local decision & actuation; adaptive sensing & control systems
- **Privacy/Security requires short-lived data: process and discard**
  - Compromised devices have no sensitive data to be revealed
- **Resilience requires distributed processing, analysis, and control**
  - Predictable service degradation, autonomy requires local (resilient) decision
- **Quiet observation and energy efficiency**
  - Vigilant sensors, transmit only essential observations, not big data streams

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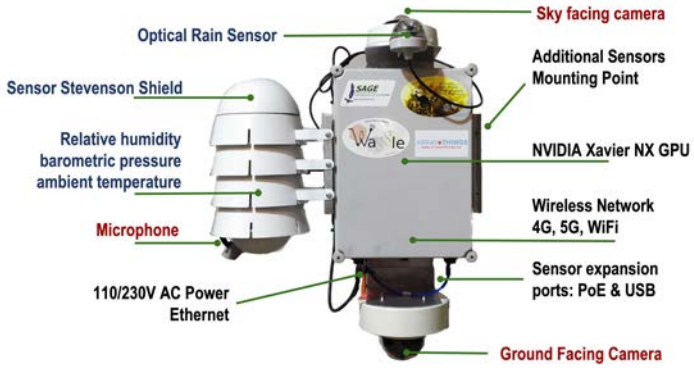
Newest Waggle Platform: Combines sensors with AI@Edge Computing to build responsive, autonomous scientific instruments

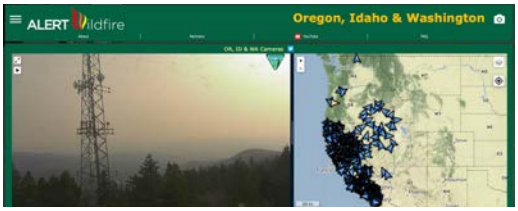


Building atop standard community software:

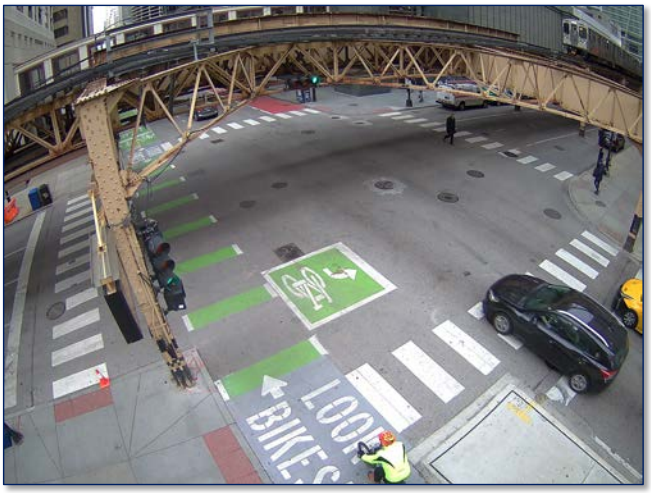
TensorFlow, TensorRT, PYTORCH, TensorFlowLite, OpenCV, docker, NVIDIA CUDA, K3S, ROS

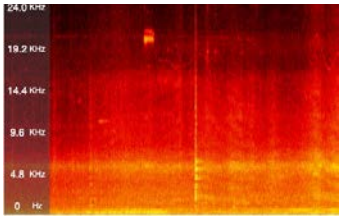
Waggle node passing freezing water/ice test chamber

Waggle node configuration for LBNL PANDA Project

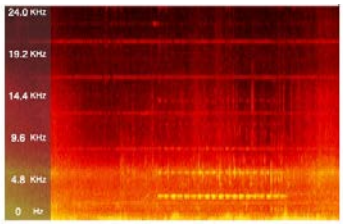


ALERTWildfire system in Oregon and Colorado, where Waggle nodes will use AI to process image data in real time for fire and smoke detection





Making data available for students to learn AI.



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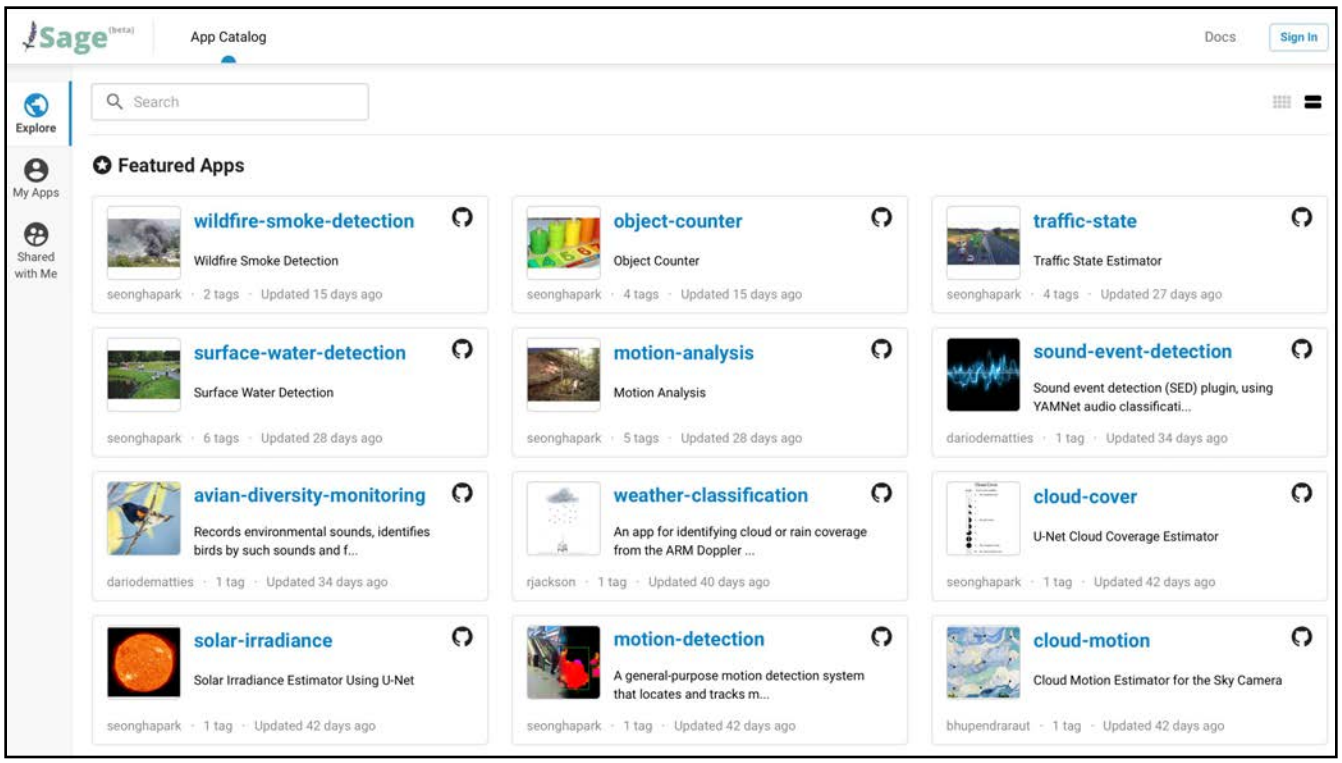

Kathleen Cagney

Director of the University of Michigan Institute for Social Research. Kate was the director of UChicago's Population Research Center and Associate Dean of Social Sciences during the conceptualization of AoT and as an AoT Co-Principal Investigator she led AoT's social and behavioral sciences team.

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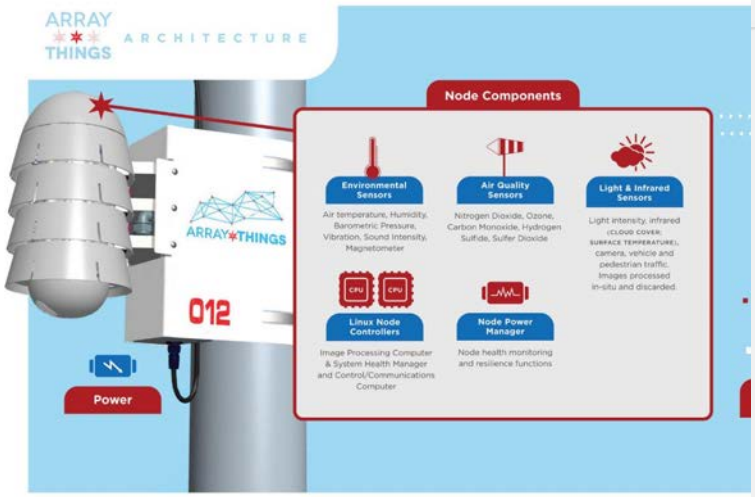
ARRAY THINGS

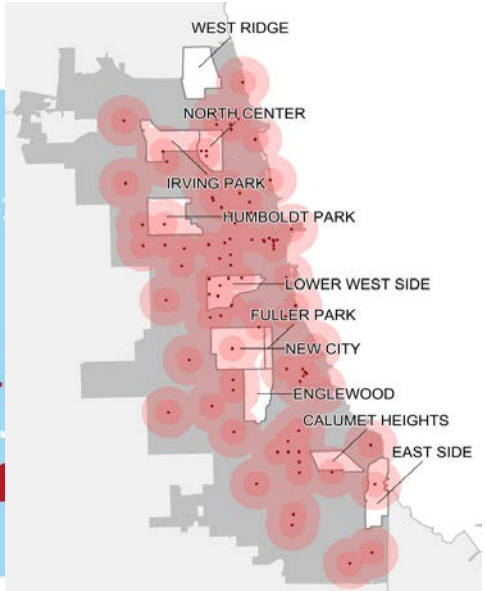
Using Edge-AI to "observe"

Chicago Health and Activity Space in Real Time *(CHART)*

AoT & Chicago Health and Activity Space in Real Time (CHART)

450 respondents age 65+ in 10 neighborhood over three waves (Summer, Winter 2018 and Summer 2019)





NORC & UChicago; English, Zhao, Brown, Catlett & Cagney (2019)

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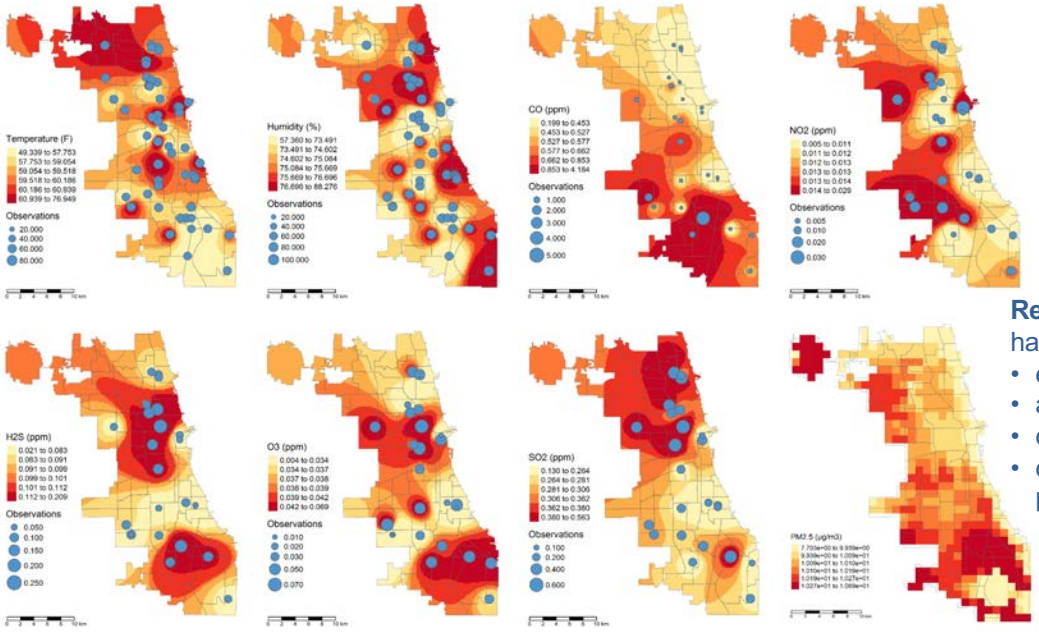
Results: **Prediction maps annual average**



Response variable: have

- emphysema,
- asthma,
- chronic bronchitis, or
- chronic obstructive pulmonary disease

Brenna Berman

Brenna was Chicago's Chief Information Officer during the formative stages of the AoT project and through its deployment. She subsequently led CityTech Collaborative, providing 'smart city' innovations and strategies for cities across the nation.

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Broad stakeholder engagement builds the extended team for long-term support and success.

The Who

- Chicago Residents
- Policy Organizations
- City Departments
- Political Leadership
- Project Partners

The How

- In-person
- In writing
- Online with forms
- Consolidated comments in one place – Madison.io
- Predictable cadence

The governance & privacy policies of public science projects must balance the input of many parties.

Array of Things Governance & Privacy Policies

The Array of Things project and its researchers value privacy, transparency, accountability, and openness. We have worked with the city, the public, and legal experts to create governance and privacy policies that reflect these principles.

AoT privacy and governance policies were developed initially in the second half of 2015 and reviewed through a workshop including legal, academic, ethics, and privacy experts from the City of Chicago, the University of Chicago, Indiana University's Trusted CI (NSF Cybersecurity Center of Excellence) in early 2016. Throughout the first half of 2016 a series of public meetings were held to engage Chicasgo residents and community groups, and after this six-month period of public comment the policies were finalized and adopted. Since that time the project has regularly reviewed the policies and found them to be effective, thus they have remained unchanged. You can download the governance and privacy policies here.

We thank the public for their valuable input during the feedback period in the spring and summer of 2016. We have published responses to all questions received online and during public engagement meetings. You can also view a final Engagement Report from Smart Chicago, summarizing the public feedback period and lessons learned from these outreach efforts.

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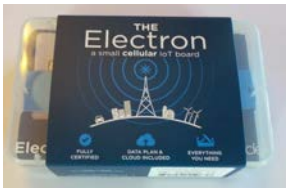
Michael E. Papka

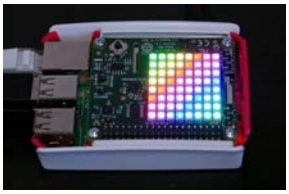
Mike is a Presidential Research, Scholarship, and Artistry Professor in the Department of Computer Science at Northern Illinois University. He is also a Senior Scientist and member of the senior leadership at Argonne National Laboratory, where he directs the Argonne Leadership Computing Facility. As an AoT Co-Principal Investigator, Mike developed innovative education programs that immersed students and early career faculty members in AoT.

TRANSLATIONAL RESEARCH: AOT AND EDUCATION

Undergraduate Research
(Citizen Science)

- Activities based on AoT
  - Hardware exploration
    - Raspberry Pi (with sense hat)
    - Particle IoT (electron)
    - NVIDIA Jetson Nano
  - Software
    - Data management
    - Running and maintaining services
    - Software development (teams)
    - Python and jupyter notebooks





James Bonasera, Thomas Franczak, May Myo Khine, Ryan Lewis, Matthew Swed, Ryan Sy, Kevin White, Alex Wills 2017 - 2019

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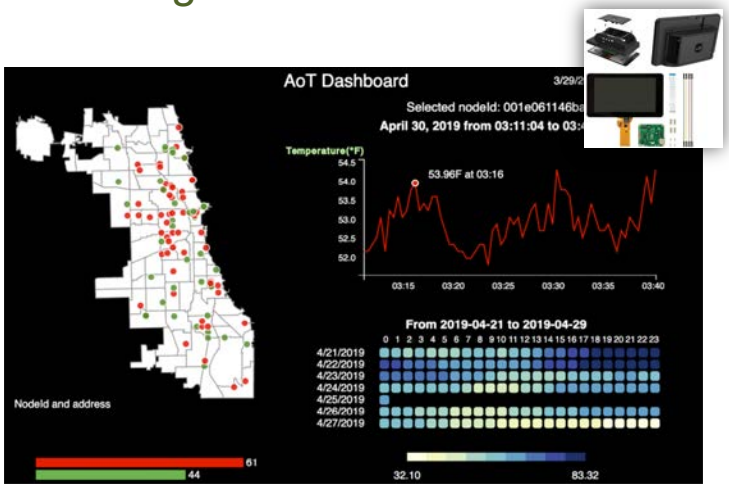
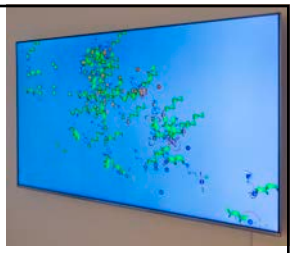
Scholarly Activity

- Undergraduate Honors Thesis
- Masters Thesis Project



May Myo Khine, Ankita (Ricky) Upadhyay#, 2019

Science as Art



DATA: BIG/-driven/Visualized. A multidimensional exhibition that delves into the array of manner in which data surrounds us, impacts us and is interpreted, 2019.

Joseph Insley*, Yamin Xu#, Ryan Lewis, May Myo Khine, 2019

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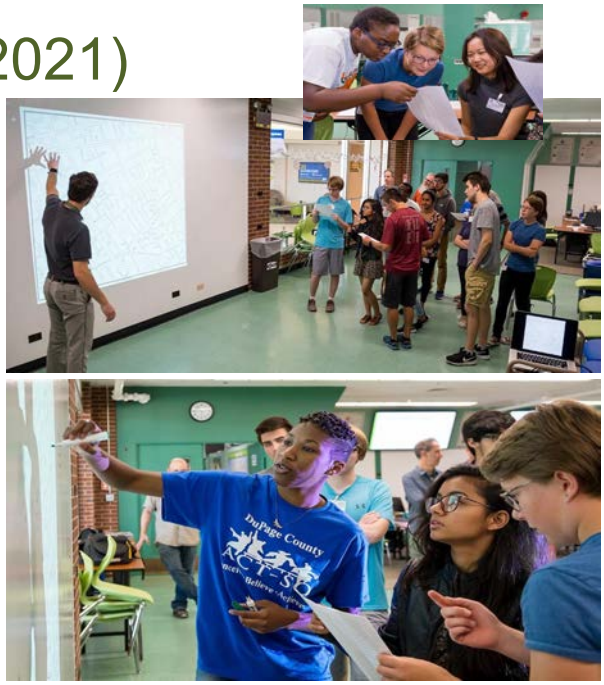
Big Data Camp (2018 - 2021)

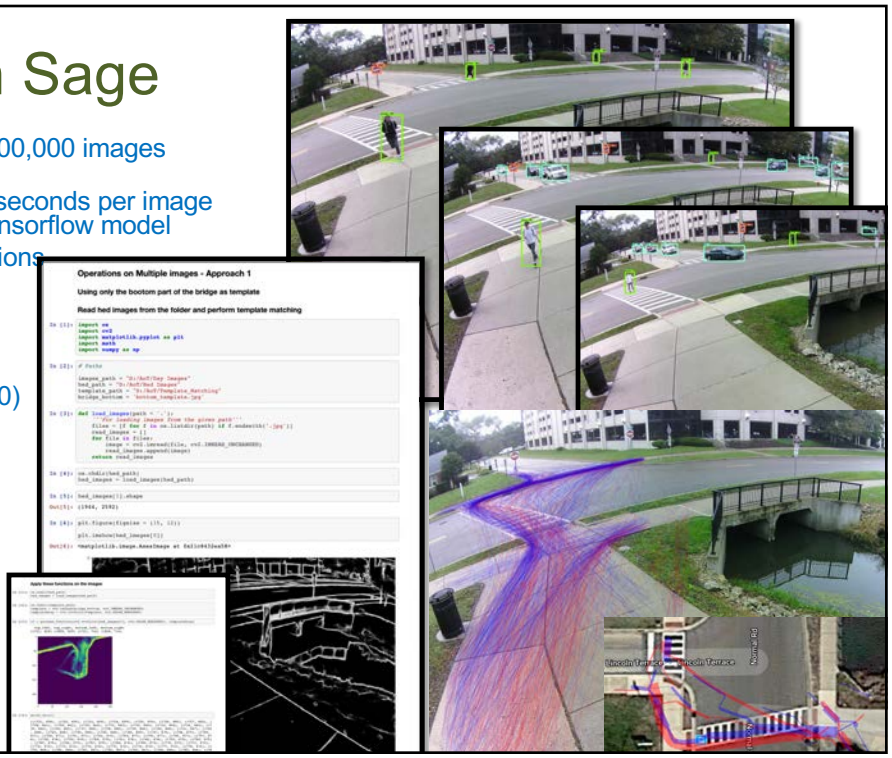
- Free, 5-day summer camp
- Participants get to learn first-hand what it's like to be a data scientist
- Students learn to visualize data and realize unexpected and amazing relationships within the data



John Domyancich, 2018 - 2021

Continuing with Sage

- In the process of labeling ~2,500,000 images
  ~two weeks of NIU AoT video data
- Test labeling of > 17,000 @ 2 seconds per image using 2 GPUs and standard tensorflow model
- Crafting classroom level questions
  - Fraction that uses crosswalk
  - Speed of cars
  - Do cars stop for people
  - Traffic and pedestrian flows
- Foundation for MS thesis (2020)
  - Project
    - Collect images
    - Process for water height
    - Extract data
    - Plot to long running service
  - Status
    - Tools for loading images
    - Determining day/night
    - Prototype water extraction



Pratool Bharti*, Dave Koop*, Emily Brown, Enkhamgalan Tamillow, Wesley Kwiecinski, Justin Derus, Priyajani Chandra#

Inspiration: Building on AoT Insights

Anne Dodge (UChicago)(Moderator)
Daniel Work (Vanderbilt)*
Marc Berman (UChicago)
Tiffany Werner (ELPC)
Douglas Pancoast (School of the Art Inst. of Chicago)

*Array of Things NSF grant Co-Principal Investigator

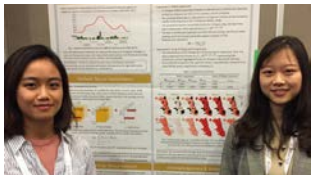
Daniel Work

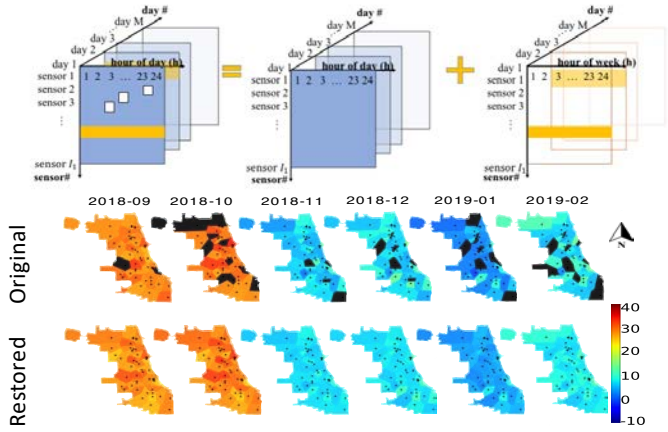
Chancellor Faculty Fellow and associate professor in civil and environmental engineering, computer science, and the Institute for Software Integrated Systems at Vanderbilt University. While at the University of Illinois, Dan was a co-Principal Investigator for the AoT project, leading the AoT transportation, infrastructure, and energy team..

[Research Sponsors: NSF, USDOE, US DOT, Tennessee DOT, views are my own]

What did Array of Things enable?

- New techniques for data cleaning for streaming sensor networks
- Developed for Array of Things, generalized to urban traffic networks





Temperature map of Chicago, recovered from Array of Things urban sensor network data

Y. Hu, Y. Wang, C. Jiao, R. Sankaran, C. Catlett, and D. Work, "Automatic data cleaning via tensor factorization for large urban environmental sensor networks," in *Proceedings of the Workshop on Tackling Climate Change with Machine Learning at the Thirty-third Annual Conference on Neural Information Processing Systems (NeurIPS)*, 2019

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Deployment at full-scale: I-24 MOTION

A scientific instrument to understand and enable

- connected and automated vehicles
- Advanced traffic management technologies
- reliability, safety, & mobility

Differentiators:

- 300 4K resolution video cameras on 4 miles of I-24
- 260,000,000 vehicle-miles of trajectory data per year
- Unlocks next generation traffic science & cyber physical systems

Prototype system construction

Prototype system is now operational; Phase 1 construction in 2022

Marc Berman

Marc is an Associate Professor in the UChicago Department of Psychology and is involved in the Cognition, Social and Integrative Neuroscience programs. Marc and his team are seeking to understand the relationship between individual psychological and neural processing factors with environmental factors. Working with the AoT team, Marc leads an NSF Smart and Connected Communities project that will test new edge AI capabilities introduced with the NSF SAGE project, while benefiting from new data from low-cost air pollution sensors in Chicago.

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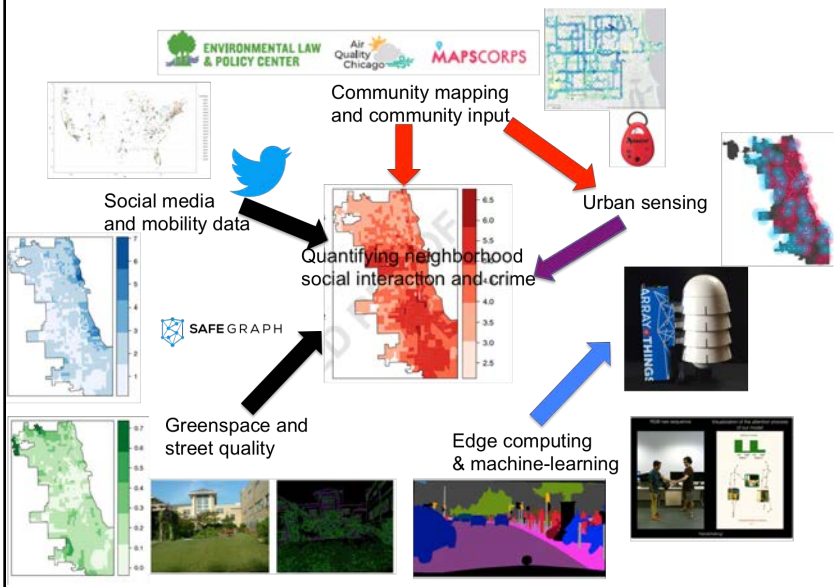
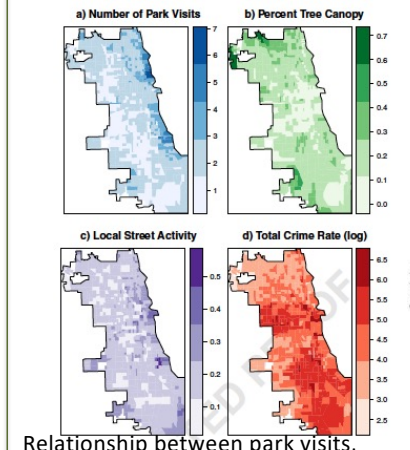
Quantifying Neighborhood Social Interaction and Crime



Project Vision

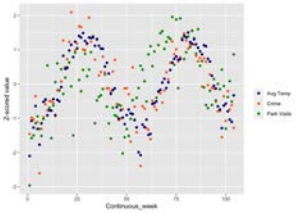
We seek to quantify the nature of social interactions in different neighborhoods based on community input, social media data, mobility data, greenspace, street quality and urban sensing data.

We plan to uncover the psychological, sociological and physical environmental factors that explain variance in social interactions. This will lead to proposed interventions to improve well-being and neighborhood social cohesion.



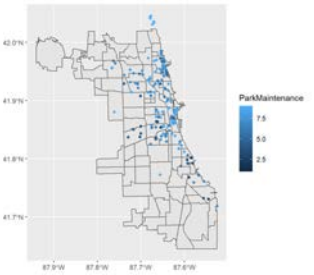
SAFEGRAPH

Replication with Safegraph data



Causal modeling with time series data

Relationship between park visits, greenspace, street activity and crime
Schertz et al., (2021) *NPJ Urban Sustainability*



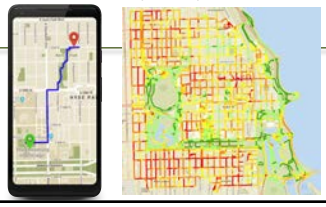
Airbeam air quality sensor

Kestrel temp and humidity sensor

Air quality measurement + Heat mapping + subjective measurements of neighborhood cohesion

ENVIRONMENTAL LAW & POLICY CENTER · Air Quality Chicago · MAPSCORPS

Data collection this summer on over 200 walking routes, with > 1200 survey datapoints



ReTUNE: Restoring through Urban Natural Experiences

Open data cam and Pedestrian counting

Creating disorder maps of Chicago using Google Streetview

Code can now be run on AoT nodes

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Tiffany Werner

Tiffany Werner is a community science organizer at ELPC, working on diesel pollution reduction and air quality monitoring. She was one of the key leaders working with Microsoft Research, JCDecaux, and the AoT team to engage Chicago community groups in the exploratory air quality sensor project with prototype sensors on Chicago bus shelters.

ENVIRONMENTAL LAW & POLICY CENTER

Air Quality Chicago

- Educating communities about what is in the air they breathe and ways to protect their health.
- Providing communities with hand-held air quality monitors to collect and understand air data, in hopes that the hands-on experience will empower them to become clean air advocates.
- Partnering and collecting data with communities that may be disproportionately affected by particle pollution
- Informing the city on how to enforce and create clean air policies that will protect public health.

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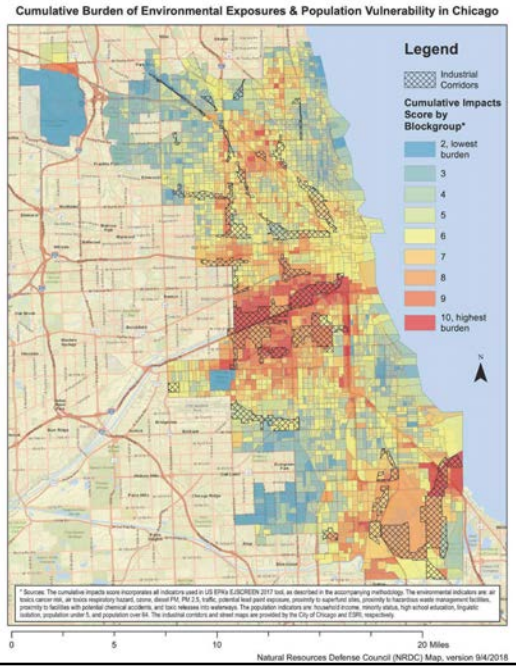
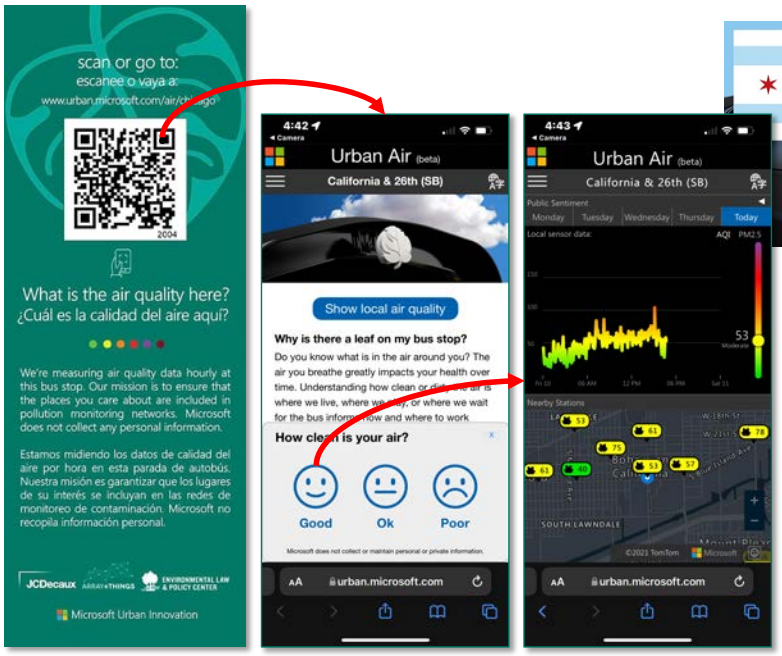
The need for more localized monitoring

- The current network of EPA sensor are not located in areas that are the most vulnerable. This leads to a system that washes out, or entirely misses local air pollution spikes.
- Localized monitoring networks (on a neighborhood or community scale) that yield quality data provides a better picture of what is happening in our most vulnerable neighborhoods.
  - E.g., Shared Air Shared Action, community led mobile monitoring with Airbeams, and Purple Air stationary monitor placement.
- City-wide networks that provide 24hr data can provide insight on what neighborhoods / communities are more vulnerable than others and when and where air pollution spikes are happening.
  - E.g., AoT and Project Eclipse



Data Legibility and Visibility Empower Participation.



Making data visible and legible to residents, and including them in design, makes Urban Planning more effective and participatory rather than merely responsive (though responsive would be good!)

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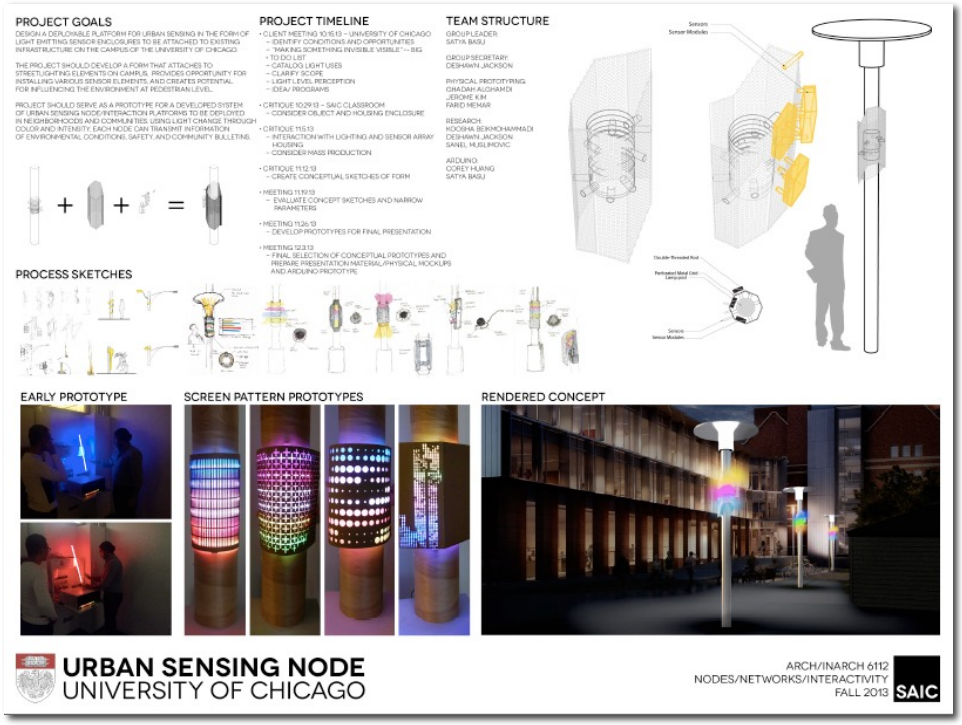
Douglas Pancoast

Douglas Pancoast is Associate Professor and Chair of Architecture, Interior Architecture and MFA(Arch) / MFA(DET) at the School of the Art Institute of Chicago. As part of the team that conceived of AoT as an urban-scale instrument, Douglas led the design of the physical form of the nodes. He also led the School of the Art Institute's collaboration with Lane Technical High School and the "Lane of Things" program.



2013 Vision

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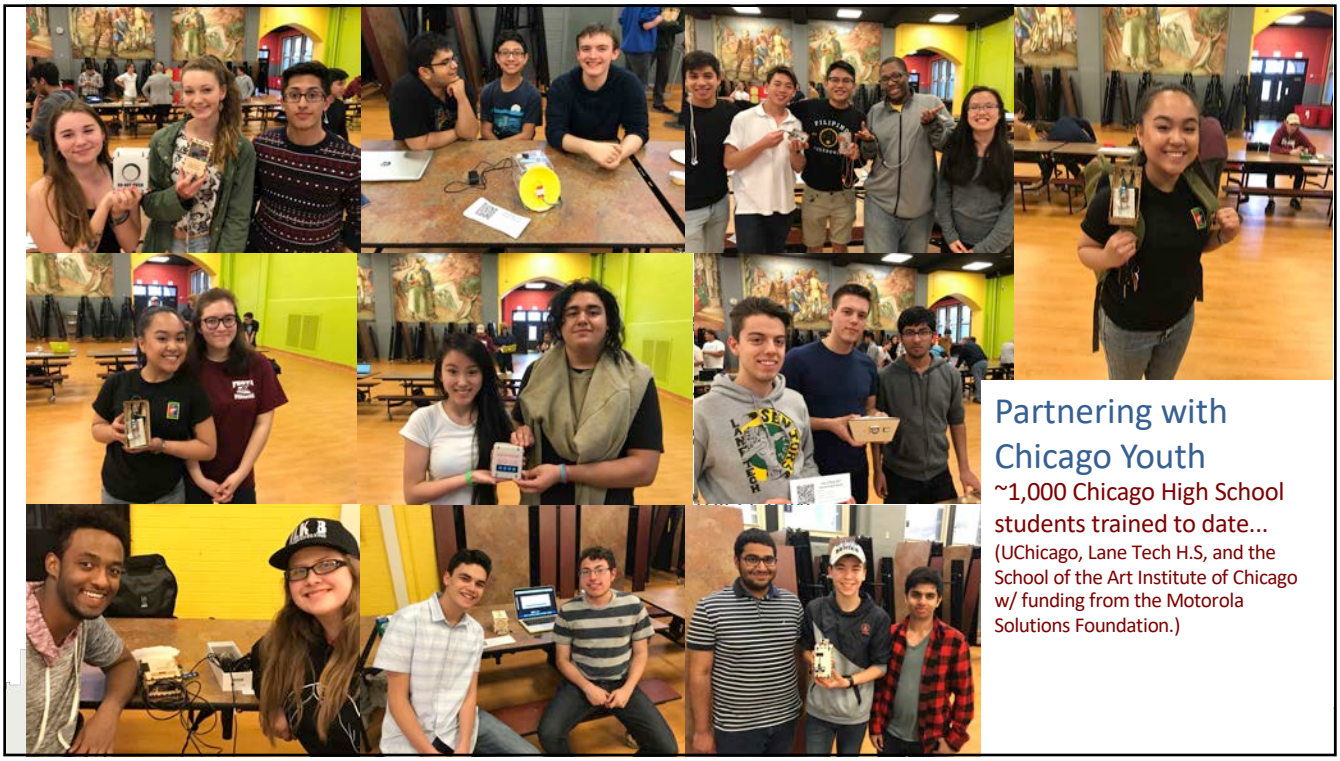

Partnering with Chicago Youth

~1,000 Chicago High School students trained to date...

(UChicago, Lane Tech H.S, and the School of the Art Institute of Chicago w/ funding from the Motorola Solutions Foundation.)

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Acknowledgements

- Array of Things was funded through a Major Research Instrumentation (MRI) grant (1532133, 2015) from the U.S. National Science Foundation (supported by Computer and Information Sciences and Engineering, Crosscutting Programs, and Engineering).
- Array of Things cost-sharing partners included the City of Chicago, the University of Chicago, AT&T, Cisco, Intel, Microsoft, Motorola Solutions, and Schneider Electric.
- Array of Things technology partners included Amazon Web Services, Crown Castle Communications, Exelon, JCDecaux, Sidewalk Labs, PDT/Astrotech, and Surya Electronics.
- The Waggle platform used for AoT was developed with funding from Argonne National Laboratory (Laboratory Directed Research and Development, LDRD), with extensions and customizations funded by the University of Chicago and through the NSF MRI grant.
- The SAGE project is funded through a Mid-Scale Research Infrastructure (MSRI) grant (1935984, 2019) from the U.S. National Science Foundation.
- Beyond cost sharing, the AoT project would not be possible without the extensive support from, and partnership with, the City of Chicago Department of Innovation and Technology, Department of Transportation, and Mayor's Office.

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