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1 Accomplishments

1.1 What are the major goals of the project?

Create a new form of cyberinfrastructure comprising an "instrument" with three specific **use modalities**:

1. Data Users. Access to high spatio-temporal measurements for a major urban area, including environmental, air quality, and indicators for various forms of activity (e.g., pedestrian or vehicle traffic flows). All data to be open and free, in multiple forms including longitudinal as well as near real time data through web portals, workflow applications, and application programming interfaces.
2. Sensor and Hardware Developers. Enable rapid evaluation and test, at urban scale, of new sensing and other hardware components.
3. Intelligent Infrastructure Developers. Support "software defined" measurements through remotely programmable edge (in-situ) computation, applying machine learning and other techniques to process images, sound, and other data and report on extracted information (e.g., flooding, traffic flows, cloud cover).

Based on the open source, modular "Waggle" hardware/software platform developed by Argonne National Laboratory, the University of Chicago, and Northwestern University, the instrument goals also included supporting these use modalities through cyberinfrastructure demonstrating **critical properties**:

4. Scaling and Resilience. Ability to scale to thousands of devices, providing reliable operation, data collection, and management approaches (and costs) that scale sub-linearly with system size, including policy that can be embedded in, and propagated through, the cyberinfrastructure.
5. Replicability. Adaptable technology to enable similar instruments to be readily constructed, at various scales (smaller and larger than the Chicago instrument) in other venues and contexts (urban and otherwise).
6. Policy and Practice to Support Cyberinfrastructure in the Public Way. Policy and process for embedding cyberinfrastructure *in public spaces*, with appropriate governance, policy, documentation, and public engagement.

1.2 What was accomplished under these goals?

1.2.1 Major Activities:

1.2.1.1 Use Modality Activities (data, sensor testbed, intelligent infrastructure testbed (edge))

1. Data: New APIs to enable application developers to access near-real time data (updated every 5 minutes). Documentation and clients for R, Python, and JavaScript are available.
2. Data: Longitudinal data website with multiple options for bulk data download (by day, week, month, year, or all-data), updated every 24 hours.
3. Data: Community tools and tutorials made available, including data parse/filter tools and multiple online tutorials (R/R-Markdown, Python/Jupyter).
4. Data: Held AoT User Workshop with over 100 participants (plus over 50 remote participants).
5. Sensors: Designed environmental sensor board with solder points to enable rapid integration of test sensors.
6. Sensors: Established a collocation test site with Cook County Department of Environmental Controls and Illinois EPA; conducted rigorous testing of PM2.5, O_3, and NO_2 sensors through a collaborating team of scientists, led by DePaul University, and from Argonne, UChicago, City of Chicago Department of Public Health, City of Portland, and Cook County.
7. Sensors: Selected new PM2.5 sensor (Plantower) based on extensive field testing and evaluation, including evaluation of reliability and results from over 4000 units deployed by collaborators at the Location Aware Sensing System (LASS) project at Academia Sinica (Taiwan).
8. Edge: Provided tutorial (at August 2018 User Workshop) covering the use of AoT edge computation capabilities (supports common machine learning frameworks, e.g., OpenCV, TensorFlow, Caffe).
9. Edge: Supported several user projects including (a) use of the upward facing camera to identify objects, differentiating between aircraft, birds, and drones (based on movement characteristics),

(b) test new flood (standing water) detection algorithms with graduate students from Northwestern, and (c)

1.2.1.2 Critical Properties Activities (scalability, resilience, replicability, policy and practice)

10. Scalability: Deployed over 100 nodes in Chicago during FY18 (a second 100 units is scheduled for installation beginning December 2018).
11. Scalability: Transitioned device manufacturing and supply chain management to a commercial partner with a build capacity of 20 units per week.
12. Resilience: Designed and tested 5th generation Waggle Manager (WagMan) with enhancements based on early 2018 deployment, including (a) improved performance in cases of significant variation in input voltage, (b) additional local storage for device performance data, (c) remote communication capabilities to enable system rebuild/restart in cases where edge Linux systems fail, and (d) additional resilience features.
13. Replicability: Finalized research agreement terms and conditions for supporting research team partnering with the University of Chicago to deploy AoT systems; established research partnerships and test sites (with 3-10 units) with University of Washington (Seattle), City of Portland, Stanford University (Palo Alto), Panasonic (Denver), City of Detroit, Syracuse University (Syracuse), and University of North Carolina (Chapel Hill). U.S. partnerships are "turnkey" with all data and systems managed in Chicago.
14. Replicability: Established general approach to non-US partnerships, where system management and data servers will be supported by local research partners. Informal agreements with CSIRO (Australia), University of Bristol (UK), National Applied Research Laboratory (Taiwan), AIST (Japan), and Instituto Tecnológico de Santo Domingo (Dominican Republic) have been established, with formal agreements in process.
15. Replicability: Documented all installation, policy, and governance strategies and materials; providing additional legal contracts, agreements, and other Chicago-specific documents to partners (not published online).
16. Policy: Partnered with multiple City of Chicago departments, community groups, and scientific research groups to finalize site selection criteria and locations for the second 100 installations.

1.2.2 Significant Results:

See also 1.1.1 above.

1.2.2.1 Use Modality Results (data, sensor testbed, intelligent infrastructure testbed (edge))

1. Data Access and APIs. Published a "version 2" API enabling developers to access data <5min from measurement. Created bulk download site with various windows of download (all data from all time; monthly, weekly, daily windows), with open source tools for extracting data such as from a given location, set of locations, or limited to a subset of sensor data sets.
2. Sensor Measurement Characterization and Evaluation. Scientists from Argonne National Laboratory and DePaul University developed a process for characterizing and evaluating data from air quality sensors, implementing these tests at an Illinois EPA site operated by the Cook County Department of Environmental Controls. Scientists compared AoT sensor readings for PM2.5, O3, and NO2 with those from the IEPA Federal Reference Method sensors, including adjustments to compensate for differences in sampling and averaging (FRM sensor readings are hourly averages, while AoT measures at 30s intervals). A preliminary report was prepared for the AoT User Workshop in August 2018 (see supplemental documents).

1.2.2.2 Critical Properties Results (scalability, resilience, replicability, policy and practice)

3. Platform Reliability. Over 100 nodes were installed in early 2018 with improvements related to moisture protection and firmware in the controller board to compensate for input power fluctuations. A formal evaluation of reliability will be done through a no-cost extension during FY19. We find multiple "failure" modes that are being investigated, including (a) unresponsive node, (b) node requiring reset, (c) sensor board failure, and (d) individual sensor failure.

4. Transition to Industry. Fully transitioned all assembly and supply chain management to local industry partner, establishing detailed manufacturing documentation as well as procedures for ordering new units in quantity while specifying design and component changes. An order for 150 units was placed at the end of FY18—100 of these will go into Chicago and 50 will go to partner cities (see 1.2.1.2 above)
5. Streamlining Public Engagement and Site Selection Process. Established a process for engaging departments and agencies city-wide as well as for engaging community groups and individual community members to request locations for installations. The process balances specific site selection with an overall goal of establishing nodes within 2km of 100% of Chicago's population and within 1km of at least 80% of Chicago's population.

1.2.3 Key outcomes or other achievements:

In addition to the activities and results noted above:

Interest from Science Groups in other Cities. With a major deployment of 105 nodes in mid-FY18 and a second 100-node deployment in early FY19, AoT continues to capture the imagination of the science and policy communities, with over 120 requests to test units in other cities around the world, coming from either cities or from research teams interested in using the platform for their research.

Lower-Cost Measurements: microWaggle. AoT node costs are roughly $3,000 per node, given the expense of sensors (and of Air Quality sensors in particular) and the resilience and packaging requirements driven by edge computing. Summer high-school and undergraduate students prototyped "microWaggle" based on commercial microcontrollers, reporting data using the same schema as AoT nodes. With microWaggle, units can be configured with one or two sensors to extend the reach of AoT at a cost of under $200 per node. Graduate students from Northwestern prototyped microWaggle for moisture and water level measurements in the Chatham neighborhood in Chicago, augmenting the AoT nodes there. Similarly, graduate students from the University of Texas-Dallas (Prof. David Lary's team) used GPS-enabled microWaggle nodes to measure air quality, in a form designed to fit in a bicycle water bottle holder.

Support for Alternate Edge Computing Hardware. The new node controller board (Waggle Manager, or WagMan) generalizes some of the edge computing interfaces so that we will be able to evaluate multiple alternatives to the Odroid units in current nodes, with a target of January 2019 for selection of upgraded edge computing systems. Hardware from Intel, ARM, NVIDIA, and other vendors will be evaluated with the new WagMan, which provides more general support for edge computing hardware. With improved edge computing power, it will be possible to do more sophisticated image processing as requested by many users, such as detecting "near miss" traffic collisions or gathering statistics on bicycle helmet use.

Machine Learning Training Data. A growing collection of hundreds of thousands of training images, taken at 15 minute intervals from all nodes, is available to computer vision researchers via a Globus website. Per the AoT privacy policy these images are controlled and the corpus cannot be published (but individual images can be published if no faces, license places, or other identifying information is removed), thus researchers must sign a data use agreement to gain access.

High School Curriculum. With four consecutive years of funding from the Motorola Solutions Foundation, the AoT team has been optimizing an 8-week high school curriculum, "Lane of Things" at Lane Technical High School since 2016. Over 450 students have been trained and the current Motorola Foundation funding supports a professional development program that has also trained teachers from an additional 12 Chicago middle and high schools. In FY19 the students will begin to use microWaggle to report their measurements using the same schema used for AoT data, and they will incorporate AoT data into their projects.

1.3 What opportunities for training and professional development has the project provided?

As in years past the project has involved 15 summer students working at Argonne and University of Chicago on systems, software, and data access projects. In summer 2018 this program was expanded to include 6 high-school students.

With funding from the Motorola Solutions Foundation for a fourth year in a row, the “Lane of Things” high school curriculum has trained over 450 students at Lane Technical High School and is being extended to 12 Chicago schools in 2018-2019 following a one-week professional development workshop for teachers during July 2018. During the school year there will be four additional one-day workshops as teachers in these schools implement the curriculum for the first time.

The team has also hosted a postdoctoral fellow from Australia’s national laboratory, the Commonwealth Scientific and Industrial Research Organisation (CSIRO), to learn the Waggle platform in order to support an initial AoT deployment in Melbourne and subsequent deployments in additional Australian cities.

Rajesh Sankaran, the computer engineering scientist who led the implementation of multiple Waggle hardware and firmware systems, was selected by Argonne National Laboratory for a 6-month mid-career professional development program based on his work on Array of Things.

1.4 How have the results been disseminated to communities of interest?

Results are disseminated through talks at conferences, the project website, publications, and the media. The project website includes access to reports on community engagement and transparent policy development, project policies, project technical details, presentations, and science and education goals. The project website, http://arrayofthings.org, keeps links to all videos and major news publications about the project, and is continually deepened with detail on policy, status, and technology.

At the AoT User Workshop in August 2018 there were tutorials as well as a round table mini-tutorial related to “lessons learned” deploying cyberinfrastructure in the public way. Led by project executive director Kate Kusiak Galvin along with Chicago’s current CIO (Danielle DuMerer) and former CIO (Brenna Berman), this round table reviewed aspects of the AoT deployment that had gone well, as well as reviewing “what we would do differently in retrospect.”

1.5 What do you plan to do during the next reporting period to accomplish the goals?

During FY19 the project will operate under a No-Cost Extension, pursuing the plans below aimed at each of the three use modalities of this new type of cyberinfrastructure, and at each of the critical properties outlined above.

1.5.1 Use Modality Plans (data, sensor testbed, intelligent infrastructure testbed (edge))

1.5.1.1 Data Users. Access to high spatio-temporal measurements for a major urban area.

The data pipeline team is working with the Center for Spatial Data Sciences at the University of Chicago to leverage their GIS portal, a set of AoT spatial data analytics tools, and tutorials, to provide users with data browsing and common graphing and mapping capabilities.

The API is being extended in FY19 to include support and test/example code for additional programming languages (currently the API supports JavaScript, Python, and R).

A second AoT user workshop is planned for summer 2019 with additional partner-provided tutorials and analysis tools.

1.5.1.2 Sensor and Hardware Developers. Enable rapid evaluation and test new components.

Current particulate matter sensors typically rely on light refraction, and are susceptible to artificially high measurements when humidity is high. Igor Paprotny (UI-Chicago) will provide a set of prototype PM2.5 sensors that use new methods (a vibrating membrane [1]), to be tested in AoT nodes at EPA sites.

At a collocation site operated by the Illinois EPA, AoT measurements of SO_2, NO_2, and PM2.5 from the Federal Reference Method (FRM) instruments are used to evaluate AoT data. Data evaluation will be extended to include CO (using an instrument on loan for 6 months from UI-Chicago). Prof. Mark Potosnak (DePaul University) and Dr. Rao Kotamarthi (Argonne National Laboratory) lead a multi-institutional team evaluating AoT air quality measurements.

In collaboration with faculty member Daniel Horton and graduate student Anastasia Montgomery from Northwestern University, AoT data is being compared to satellite data from TROPOspheric Monitoring Instrument (TROPOMI, http://www.tropomi.eu). TROPOMI measures O_3, SO_2, NO_2, and CO. In 2019 the TEMPO satellite (http://tempo.si.edu) will launch, and the AoT air quality team has begun discussions with the TEMPO team to use their high-resolution (5km by 8km) measurements of O_3, SO_2, and NO_2 to evaluate AoT data.

1.5.1.3 <u>Intelligent Infrastructure Developers</u>. Support "software defined" measurements.

New edge computing hardware will be selected in early 2019 for inclusion in the next installation of nodes beyond the 200 that will be in place in early FY19.

1.5.2 <u>Critical Properties Plans (scalability, resilience, replicability, policy and practice)</u>

1.5.2.1 Scaling and Resilience.

As of the end of FY18 some 100 nodes were installed. In December 2018 a second round of 100 nodes will be installed, and in summer 2019 a third round of nodes will be installed. We are finalizing budget and cost projections, but anticipate that 30-50 of these nodes will be full AoT nodes.

We are also investigating the use of lower-cost, limited function nodes with PM2.5, Temperature, Relative Humidity, and Sound capabilities, costing less than 10% of the cost of a full AoT node. We have prototyped this system and are exploring the potential for 200-300 of these nodes to be deployed through a partnership with JCDecaux, the outdoor advertising and street furniture company that operates 2100 bus shelters in Chicago (most of which have power available).

1.5.2.1 Replicability.

During FY17 we designed a partner program whereby research institutions can purchase AoT nodes, to be managed by the University of Chicago, and requiring that the data (open, free) and privacy policies are identical to the AoT instrument's policies in Chicago.

During FY18 there were six partner projects deploying AoT nodes (University of Washington, City of Portland, Stanford University, Panasonic (Denver), Syracuse University, and the University of North Carolina). By January 2019 several additional partners will begin deployment, including the City of Detroit, Vanderbilt University, Georgia Institute of Technology, CSIRO (Australia's National Laboratory, Melbourne), and National Applied Research Laboratory (Taiwan, Taichung City). We are documenting the support requirements and the logistical aspects of deployment, ranging from public interaction to permitting and installation, to include in our final report.

1.5.2.2 Policy and Practice to Support Cyberinfrastructure in the Public Way.

The tutorial on deployment of instruments in the public way, taught at the first user workshop in August 2018, will be updated, along with insights noted above in §1.5.2.1.

2 Products

2.1 Journals or Juried Conference Papers

Catlett, C. E., Beckman, P. H., Sankaran, R., & Galvin, K. K. (2017). Array of things: a scientific research instrument in the public way: platform design and early lessons learned. Paper presented at the Proceedings of the 2nd International Workshop on Science of Smart City Operations and Platforms Engineering.

Status = ACCEPTED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

2.2 Audio or Video Products.

Many videos were produced by third parties including a video done for SC17 in conjunction with an AoT-driven plenary panel and an in depth profile of the project by BBC Click and a highlight video for Supercomputing 2017.

2.3 Websites

2.3.1 City of Chicago Public Engagement Report

http://arrayofthings.github.io/engagement-report.html

Report detailing public engagement efforts, goals, and results. Public engagement objectives were to inform residents about the instrument goals and capabilities, discuss privacy concerns, and provide details on policies. An overarching objective was to position the instrument as a community "asset" as distinct from a sterile device or a surveillance program.

2.3.2 FAQ on Privacy and Policy and Feedback

http://arrayofthings.github.io/policy-responses.html

Exhaustive (regularly updated) FAQ that addresses all of the public comments and suggestions, initially taken from public meetings, email, web forms, and multiple online options for commenting on draft policies (including the OpenGov Foundation's Madison site).

2.3.3 Node Location Request

https://docs.google.com/forms/d/e/1FAIpQLScIG6YevqzWW4d1U0eH1D2tNSQuHnlng6AMrlDE4V8Gf136qQ/viewform

Form for use by residents or others requesting that AoT place one or more nodes in a specific location or neighborhood. Allows a non-scientist to articulate a science question in terms of goals, type of measurement, and locations.

Note this form is linked from the friendlier URL of the main project site, http://arrayofthings.us

2.3.4 Plenario System Overview

https://github.com/UrbanCCD-UChicago/plenario-stream/wiki/System-Overview

Extensive system documentation for the Plenario system that will serve as a key portal for all AoT instrument data. The site is necessary to support developers wishing to create portals, analytics tools, or applications that use instrument data.

2.3.5 Project Information Portal

http://arrayofthings.github.io

Main project website with links to all policies, technical documentation, press, etc.

2.3.6 VIDEO: BBC Report on Chicago Array of Things]

http://www.bbc.com/news/av/technology-39229221/air-quality-tracker-for-chicago-to-roll-out-city-wide

An update on air quality and Array of Things, published March 2017 and following a previous BBC profile on the project:

http://www.bbc.com/news/av/technology-32511363/key-to-chicago-s-quality-of-life-the-array-of-things

2.3.7 VIDEO: AoT Technology and Privacy

https://www.youtube.com/watch?v=pFL5QNwgs6A

Short video focusing on the manufacture, technology, and privacy of the AoT instrument. The video was developed specifically to help residents understand the privacy protections built into the device and into policy.

2.3.8 Waggle Platform Software Site

https://github.com/waggle-sensor/

Developed site to document the open source software stack, and eventually the hardware specifications, for the instrument. This site is also essential to engaging the research and development community in evaluating and hardening the software stack.

3 Impacts

3.1 What is the impact on the development of the principal discipline(s) of the project?

We have continued to see a growing level of demand for a general purpose, reliable sensor and embedded systems platform in the science community. The number of cities and research teams requesting information on deploying AoT has grown beyond 120, with six partners as of FY18 and this will more than double in FY19 (see §1.5.2.1) To support this, we have developed a business structure at UChicago that involves a one-year research agreement where partners pay for nodes in context of a “turnkey” system, with costs for support built into the purchase pricing.

With the publications about the platform design and early lessons this year and the Waggle platform itself last year we also contribute to areas ranging from reliable embedded systems to computer vision (in that the platform runs standard libraries, ultimately offering computer vision experts an urban-scale computer vision instrument with 1,000 cameras).

3.2 What is the impact on other disciplines?

Co-I Kathleen Cagney (UChicago) has engaged *social scientists* from Ohio State University, UChicago, and NYU to explore collaboration with computer scientists on “observations” whereby social scientists would describe types of objects (person walking baby) or events (groups lingering in frame) that might be detected through computer vision techniques. Senior personnel Rob Jacob (Argonne) has expanded our *air quality and atmospheric sciences* team to include collaborators working on air quality sensor evaluation (Mark Potosnak, DePaul; Rao Kotomarthi, Argonne, Pinaki Banerji, Cook County, Christine Kendrick, City of Portland) as well as *environmental scientists* exploring the use of image processing to *detect flooding* (Aaron Packman, Northwestern; Nicola Ferrier, UChicago), or extending the AoT platform through celular networks to *connect moisture and flow sensors*.

Co-PI Daniel Work (Vanderbilt) is working with the City of Nashville to plan a major AoT instrument focused on mobility research, while collaborator Dan O’Brien, a social scientist from Northeastern University, has proposed an AoT instrument in Boston focused on *social and behavioral sciences*.

The privacy policies continue to be of interest to other projects as examples of community engagement and balancing science and privacy needs.

3.3 What is the impact on the development of human resources?

The School of Things (formerly Lane of Things) high school program, outlined earlier, is a key component to developing human resources. The curriculum has been developed by Kate Kusiak Galvin (UChicago), Douglas Pancoast, Satya Mark David and Robb Drinkwater (School of the Art Institute of Chicago), and Dan Law and Jeff Solin (Lane Tech High School). Over 450 high school students have been trained in three consecutive years, and a dozen Chicago teachers have taken a professional development workshop created by the team.

The summer program was expanded in 2018 with a more formal component for high school students, and as with past summers 12-15 undergraduate and graduate students participated in a 12 week program. The students were supervised project investigators Pete Beckman and Charlie Catlett, along with senior personnel Rajesh Sankaran. Additionally, we have assigned 2-3 students each to all of the software and hardware developers on the project—early or mid-year professionals—in order to provide them with supervisory experience.

Finally, Co-PI Mike Papka created a team of undergraduate students at Northern Illinois University who developed a set of Jupyter notebooks that form a new online Python tutorial on AoT data analytics.

3.4 What is the impact on physical resources that form infrastructure?

These are covered in the supplemental documents (AoT User Workshop Report), but it is important to note that AoT is a unique urban-scale instrument that supports both measurements at unprecedented spatial and temporal resolution and edge computing experiments such as data reduction, image and sound analytics, or video analytics. As such, AoT can be seen as complementing other measurement infrastructures such as EPA sites and remote (satellite) sensing infrastructure.

3.5 What is the impact on institutional resources that form infrastructure?

The AoT project has been the impetus behind relationships between Argonne and UChicago CDOT, DOIT, and new relationships with deputy commissioners and department heads in the Departments of Public Health, Planning and Development, Buildings, Parks, and Water-related agencies. During FY18 these relationships extended to county and state agencies including the Cook County Department of Environmental Controls, the Illinois EPA, and the Illinois Department of Transportation (IDOT) as well as key regional planning entities such as the Chicago Metropolitan Agency for Planning (CMAP). For instance, IDOT requested that several AoT nodes be located on at-grade rail crossings so that computer scientists could analyze the traffic impact of rail crossings, with the potential to expand the program to hundreds of rail crossings throughout Illinois.

3.6 What is the impact on information resources that form infrastructure?

This year, with critical mass of data available from the first 100 nodes, multiple GIS groups have engaged from UChicago, Northern Illinois University, and the University of Illinois to explore incorporating AoT data into their GIS portals and resources. By piggybacking on the NSF-funded Plenario system (NSF-1348865, http://plenar.io) we are able to integrate sensor data with other urban data, such as 311 calls, crimes, permits, or inspection data.

3.7 What is the impact on technology transfer?

We have transferred the supply chain management and assembly/test of AoT units to a Chicagoland electronics partner, Surya Electronics (the firm that also fabricates our circuit boards). All software for the nodes, data pipeline, and central server functions is open source and published in Github (https://github.com/waggle-sensor) and hardware specifications for circuit boards and connections will be published in FY19 once we complete detailed system evaluation of the 5th generation controller board (WagMan) through the installation of 100 units beginning December 2018.

We have established a research partnership program whereby we can support AoT projects in a sustainable fashion, with a “turnkey system” approach with centrally managed nodes irrespective of geographic location and a more extensive partnership program enabling non-US partners to operate the full system of data and management servers locally. These partnerships include agreements that require that any and all AoT projects adopt both the open/free data policy and the privacy policies. (see §1.5.2.1)

3.8 What is the impact on society beyond science and technology?

The near weekly contacts from students and faculty interested in learning more about the project and doing data analytics or machine learning projects, and from cities and universities interested in building AoT-like infrastructure reveals an increasing need for a platform that can be rapidly deployed in cities, focused on specific questions in particular neighborhoods, to provide insight into challenges, to provide ongoing measurement of conditions, and/or to evaluate the impact of major urban development projects. Today these projects are extremely costly and tend to involve bespoke systems that are either academic-generated (not reproducible) or proprietary (not producing open data; not available to support innovation from the science community.