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A Novel Approach to Toxic Gas Detection using an IoT Device and Deep Neural Networks

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About the Authors

- We are Seniors at Danbury High School in Danbury, Connecticut. Our career interests are in inventing, building and commercializing pervasive, intelligent IoT systems at scale
- We Co-Founded ExaSense Technologies Corporation (ExaSenseTech.com – under construction) where we developed working prototypes of Gas sensor array nodes with WiFi connectivity to demonstrate DNN based pattern recognition as an alternative technology to detect toxic/flammable emissions.
- We also Co-Founded the AI Club and the IoT Club at Danbury High School during our Junior Year with the goal of getting students excited about working with IoT and AI hardware while pursuing career opportunities in as they unfold.

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Outline

- Fire and Health hazards of cigarette emissions and other toxic, flammable gases
- Problems with conventional gas detector technology – too little, too late
- Our Proposal: Use Deep Neural Networks to recognize patterns in changes of concentrations in component emissions
- Wirelessly connected Microcontroller with Sensor Array to train and infer – fast, discriminating, lower cost
- Measurements to demonstrate reproducibility, speed of source identification and accuracy at much lower toxic gas concentrations
- Ability to classify and detect different levels of toxicity and flammability
- Hardware architecture and its scalability for connected and pervasive use
- Conclusions and Acknowledgements

Cigarette Smoke Health Hazards

- Serious Health Hazard – cause for over 41,000 deaths each year and one of top 3 causes of Illness in the US
- The single most preventable cause of illness and premature death in the US
- Chemicals released from smoking known to be harmful – Hydrogen Cyanide, Formaldehyde, arsenic ammonia, benzene, vinyl chloride etc.
- This toxic and carcinogenic mixture is probably the most significant source of toxic chemical exposure and chemically mediated disease in humans
- Secondhand smoke exposure can increase risk of lung cancer, heart attack, high blood pressure etc.
- **The Single biggest reason** cigarette smoke remains a health hazard is because it cannot be detected early when concentrations are low or discriminated accurately from other sources of CO

Cigarettes also a Fire Hazard

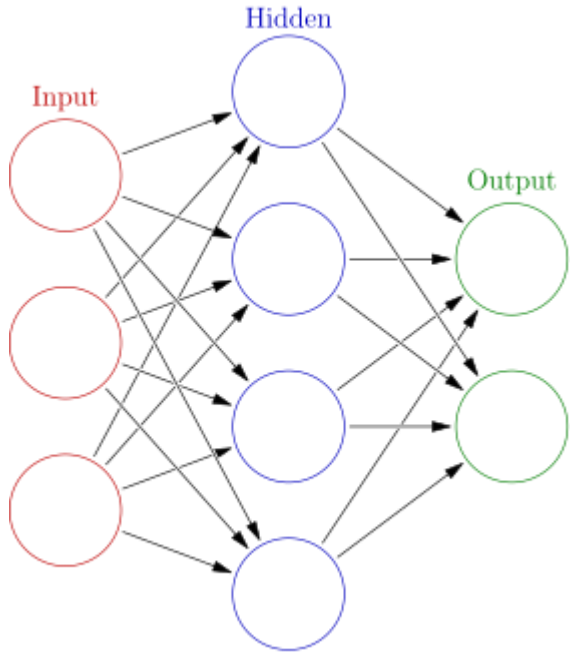
- A Serious Fire Hazard – one of top 5 causes of Fires in a home
- 18,000 structure fires each year from cigarettes causing 1 in 4 Home Fire deaths and 1 in 10 home fire injuries – NFPA
- From unextinguished, undetected cigarette butts

Conventional Smoke and Fire Detectors

- 2 out of 5 deaths result from fires in properties with working smoke alarms
- 23% of deaths caused by Fires where smoke alarms are present but intentionally disabled due to false alarms
- Conventional smoke/fire detectors built to respond to CO poisoning – requiring either much higher concentrations or longer time periods (at 50 – 100 ppm concentrations) of exposure to CO
- Toxic gases from cigarette smoke need much less time to injure vulnerable people – in hospitals, the workplace and schools and are at much lower concentrations in unextinguished cigarette butts
- Cigarette smoke must be detected early and at very low concentrations
- Cigarette smoke must also be discriminated from other less toxic sources of smoke/CO such as burning food, wood or coal

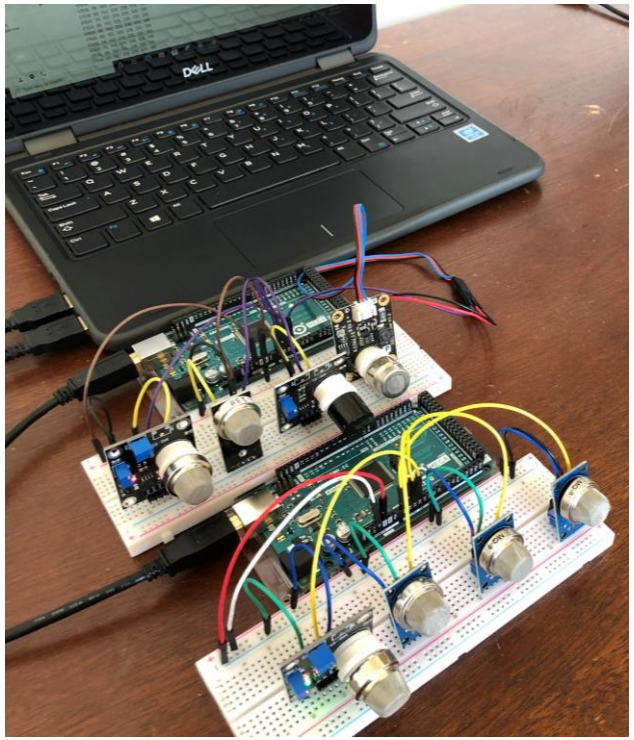
Patterns and Classifiers – fast, accurate and inexpensive

- Sensors that act alone in conventional detectors rely solely on CO or other sensors that trigger only with sufficiently high concentrations
- At low concentration thresholds in detector, the CO densities from nominal sources of CO can trigger false alarms
- *Changes in concentrations* of cigarette smoke component emissions are patterns that can be recognized by neural networks
- Even from a single cigarette in a room over 650 sq feet large with 10+' ceilings – DNNs detect a cigarette in less than 4 minutes (measurements reported in this work)
- The patterns of changes in concentrations detected by an array of sensors can recognize other toxic emissions as well in the same room



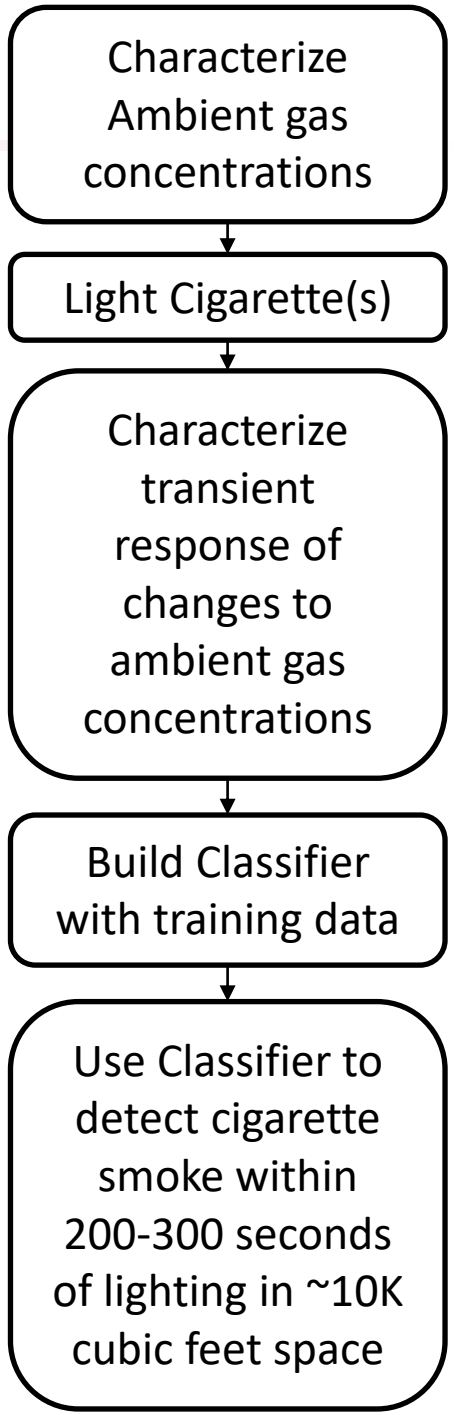
Hardware used

- 8-b RISC Microcontrollers (ATmega2560 in the Arduino mega Dev Board) concurrently support 16 sensors to collect training data
- Conventional Sensors used to detect a broad range of gases from *formaldehyde, benzene, ozone, hydrogen sulfide gas, ammonia, hydrogen, LPG, CO, CO2, methane, Butane, propane, alcohol, acetone, toulene, alcohol, smoke, natural gas*
- Conventional sensors used consume significant current (150 mA/sensor at 5V) to heat sensors before they can function.
- Dev Board sources insufficient current to support all 14 sensors used to train neural network, so three 'off-the-shelf' Dev Boards engaged to build this prototype
- Sensors sampled once every second to balance size of dataset Vs accuracy delivered
- NodeMCU WiFi module used to drive sensed data wirelessly for training and/or inference



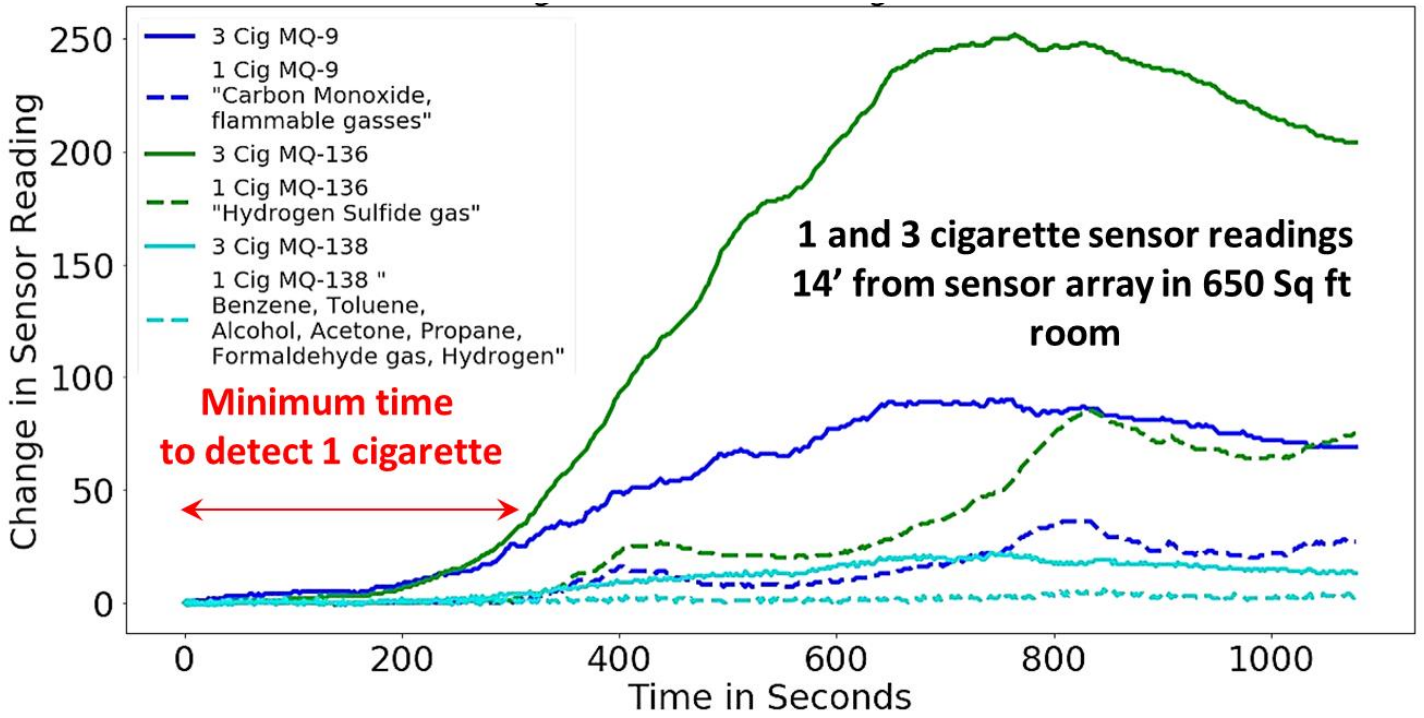
Measurement Methods

- Large room: 32’ x 20.3’ (garage) with 10.5’ ceiling – 650 Sq ft, ~ 7000 cubic feet
- Flush air in garage with multiple exhaust fans, close doors, verify unchanging sensor readings as representative of environment
- Light cigarette, emulate ‘puffing’ using bulb syringe over 10 minutes, measure changes in sensor readings
- Repeat using 3 cigarettes to build classifiers corresponding to different toxicity cases
- Extinguish cigarette, continue sensor measurements for another 10 – 500 minutes to characterize cigarette smoke ‘residue’ post extinguishing.
- Classifiers using this data can detect cigarette smoke in previous 24 hours after cigarette extinguished – useful in hospitals, hotels, schools to classify toxicity of spaces to be used by different people



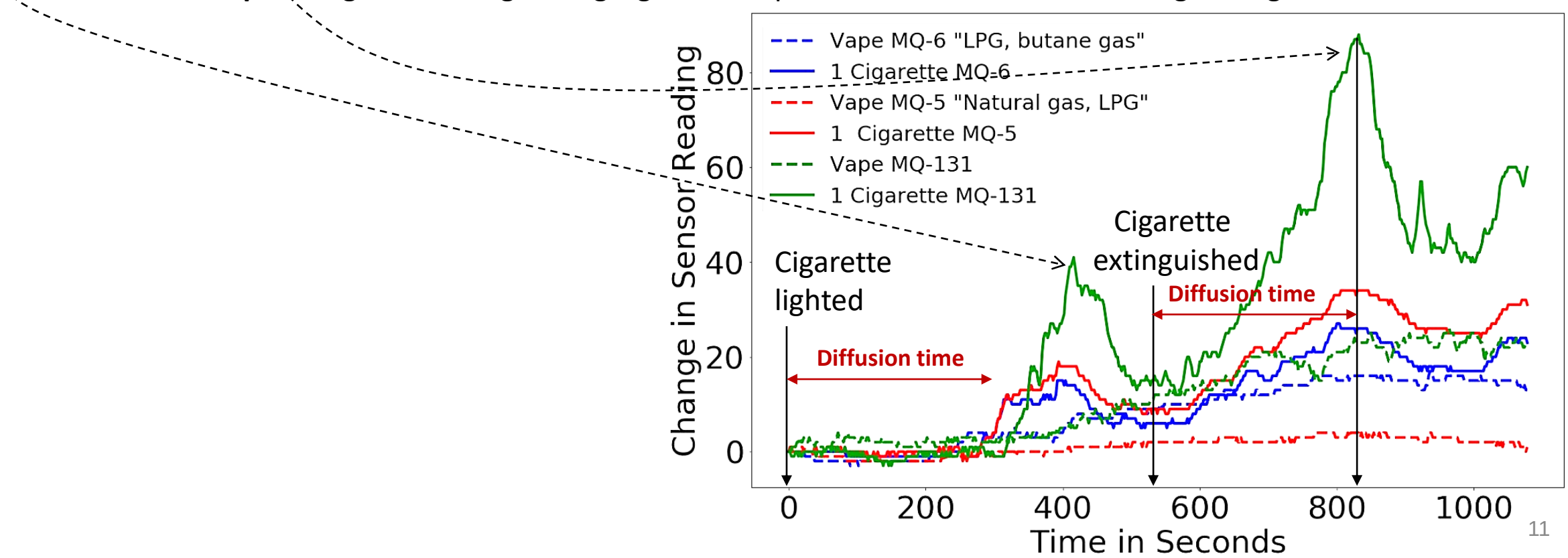
Speed, Reproducibility & Consistency of Cigarette Detection

- Sensors placed in middle of **650 Sq Ft room** and cigarette(s) at corner **(~14' away**)
- Sensors detect changes in gas concentrations within 200-300 seconds - **limited by diffusion time of emissions to sensor from 1 cigarette**)
- Changes in sensor readings **sufficient for Classifier to detect a single cigarette** in the room
- Measurements **demonstrate reproducibility of diffusion time and consistency in changes to** sensor readings
- Use of 1 Vs 3 Cigarette training data can enable **classification of different levels of toxicity**



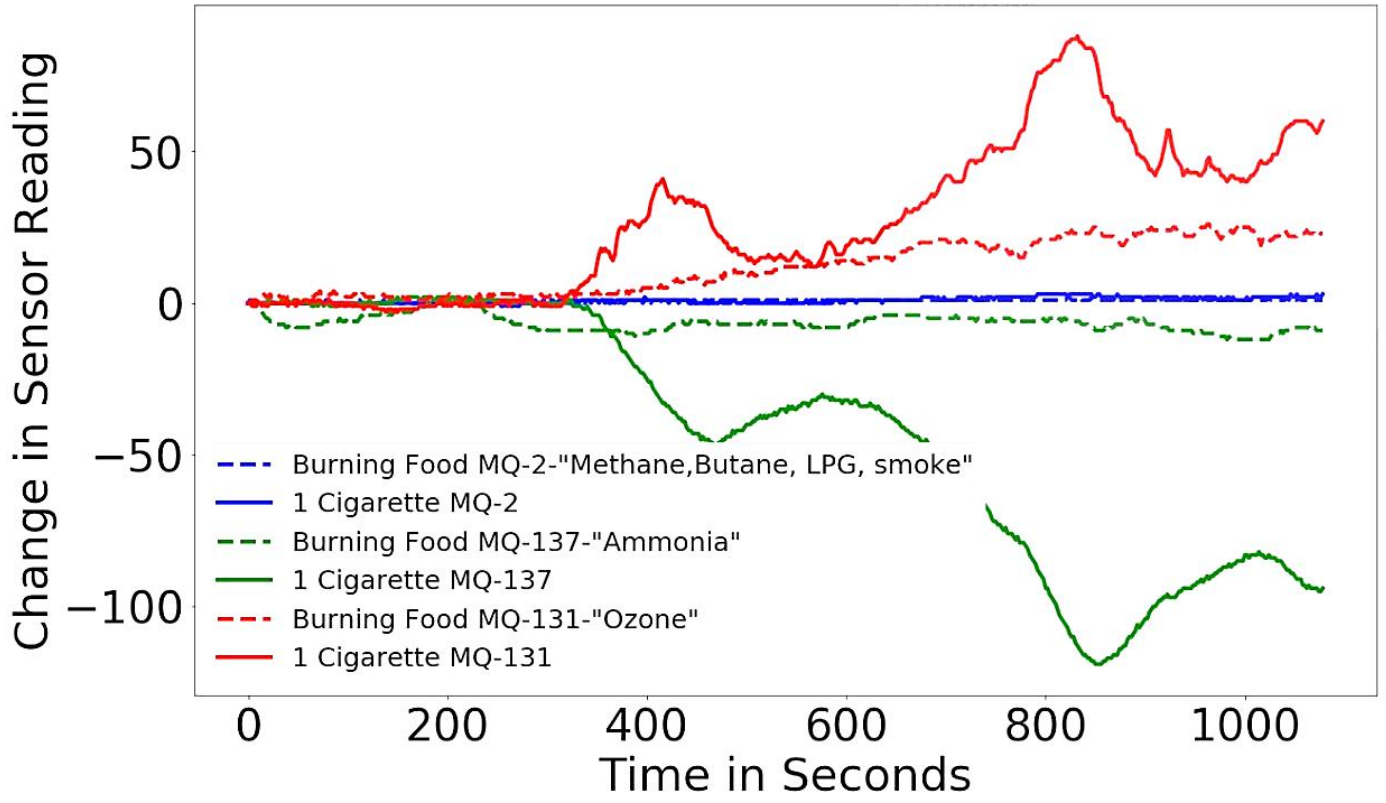
Cigarette Smoke Vs Vape Discrimination

- Sensor array response to Vape is similar to Cigarette emissions (both are comparably toxic/destructive)
- Changes registered in sensor array are different – patterns can be discriminated by Classifier (MQ5 responsive to CO as well
- Two peaks observed at very small changes in concentrations (from a single cigarette/vape)
  - **First Peak** registers initial contact of sensors to cigarette/vape emissions followed by diffusion away from sensor
  - **Second peak** registers extinguishing cigarette/vape, a Diffusion time after extinguishing at the Sensor



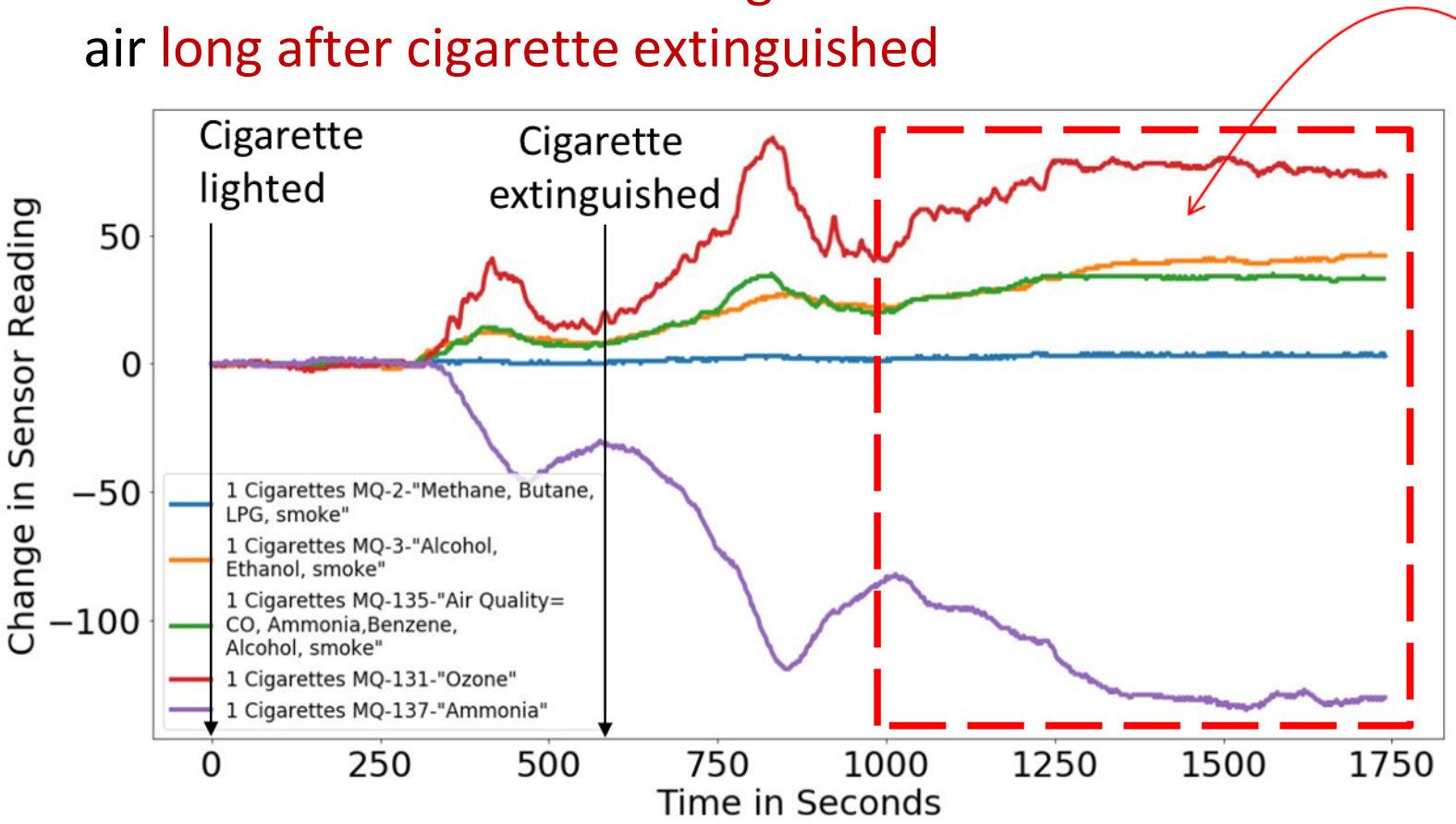
Cigarette Smoke Vs (burned) Cooking Food Emissions Discrimination

- Emissions from Burning Food *relatively harmless* but trips smoke/CO detectors anyways
- Neural Network is trained to recognize patterns from burning food and discriminate it from Cigarette/Vape emissions
- Use of Pattern Recognition eliminates 'False Alarms' from CO detection in ambient when conventional detectors are calibrated to trigger at low CO concentrations



Classifiers to Detect Residue from Past Emissions

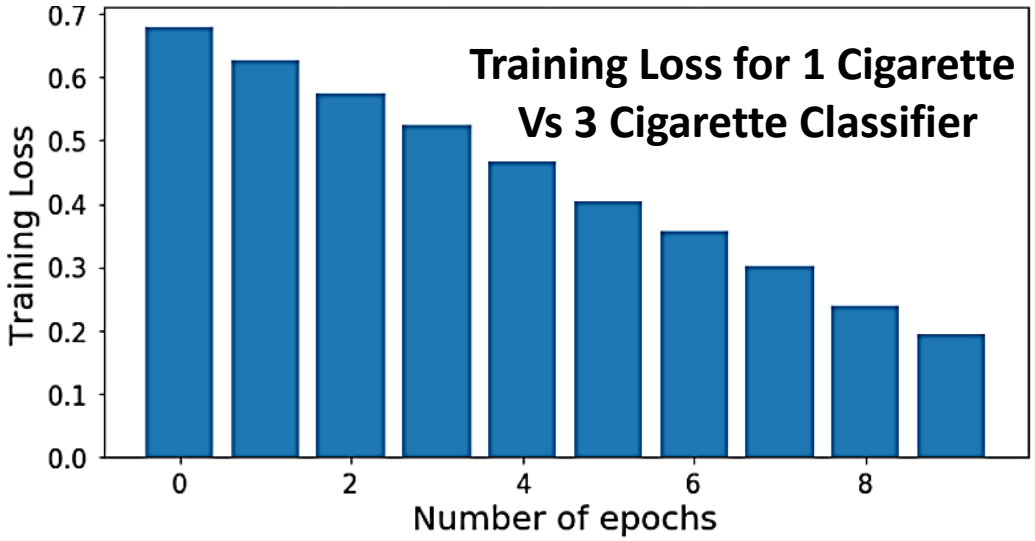
- Hotels, Hospital rooms, Workplaces, Schools used by different people at different times
- Before people use space, cigarette residue from previous users of same space can be detected using our Classifiers
- Characterized as 'Post Extinguish Period' where toxic emission components remain in air long after cigarette extinguished

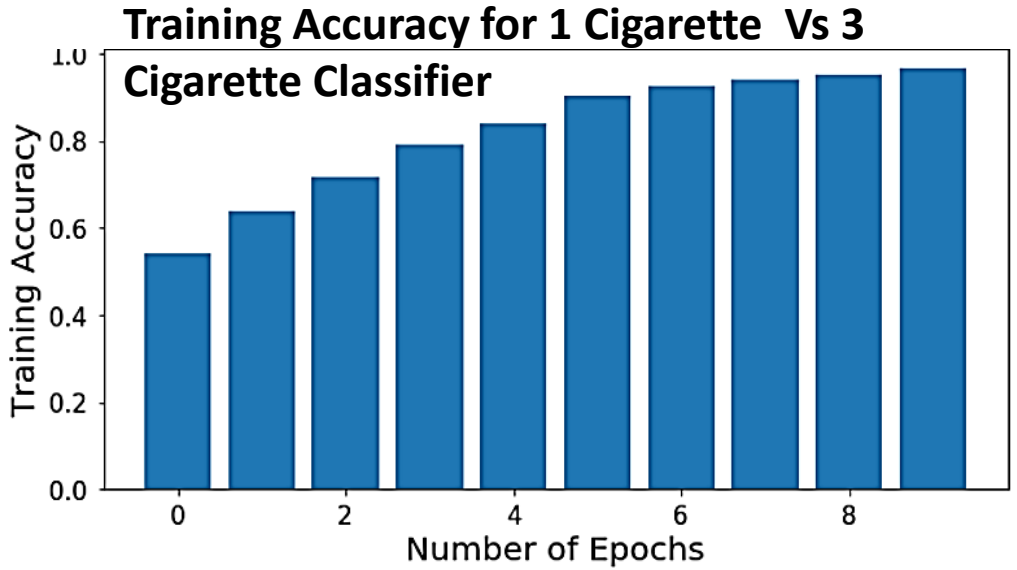


Signature pattern of Cigarette residue lingers for a long time unless space 'deep cleaned'

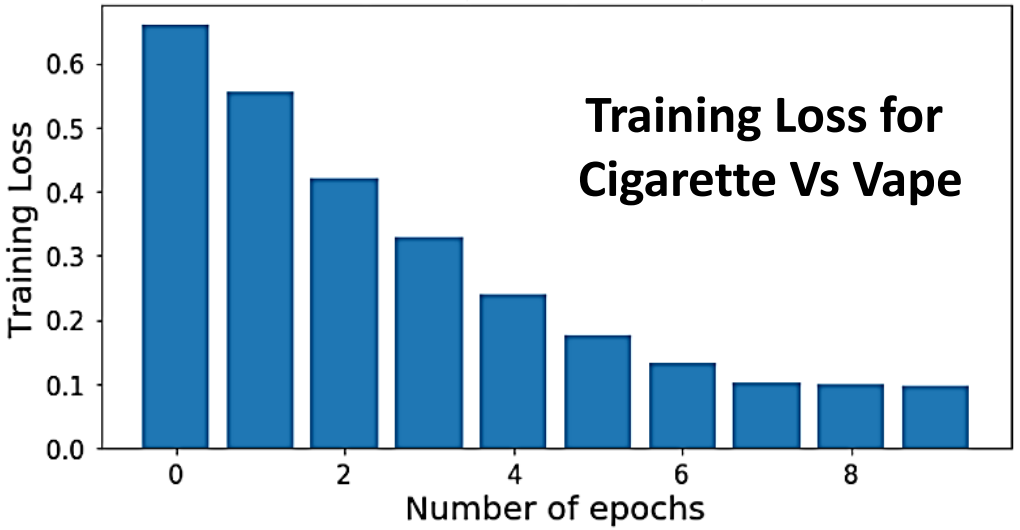
Training Loss & Accuracy of 1 Vs 3 Cigarette Classifier

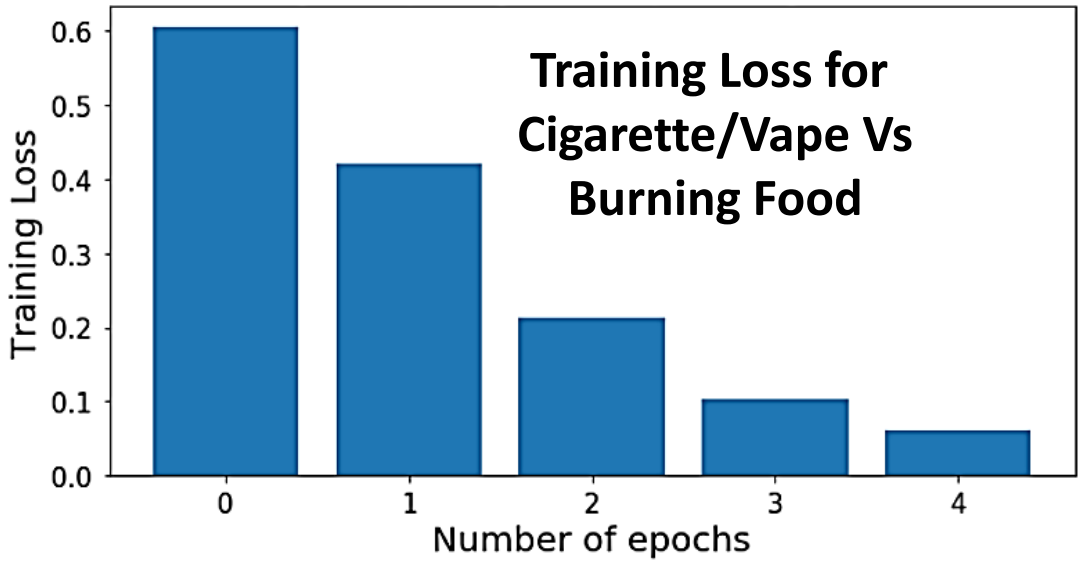
- We built Classifiers:
- Toxicity of a given source – 1 or 3 Cigarettes
- Discriminate between Cigarettes, Vape and less harmful sources such as Burning Food, Charcoal etc.
- These deliver the key requirement on neural network based sensor arrays to recognize toxic gases fast, accurately and at lower cost when sensing at scale



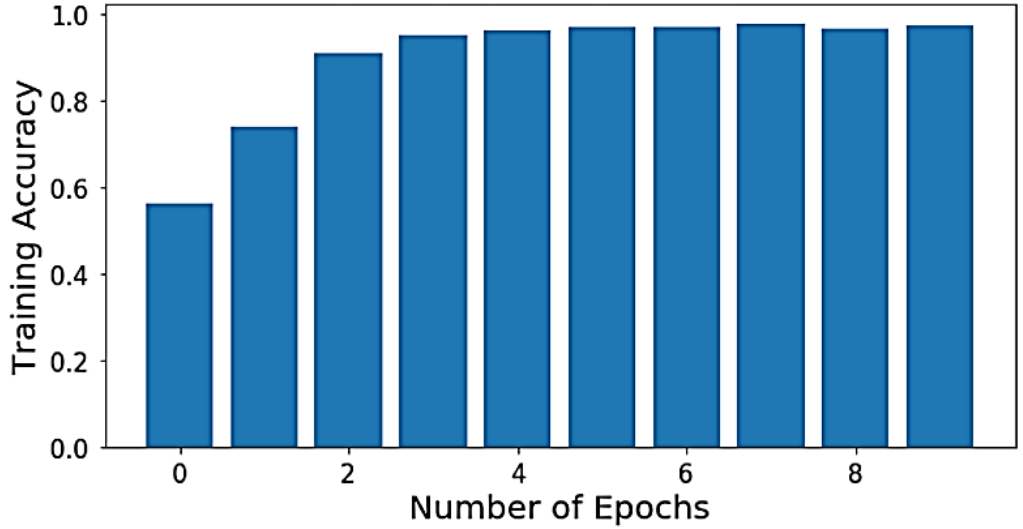


Training Loss & Accuracy of Source Detection

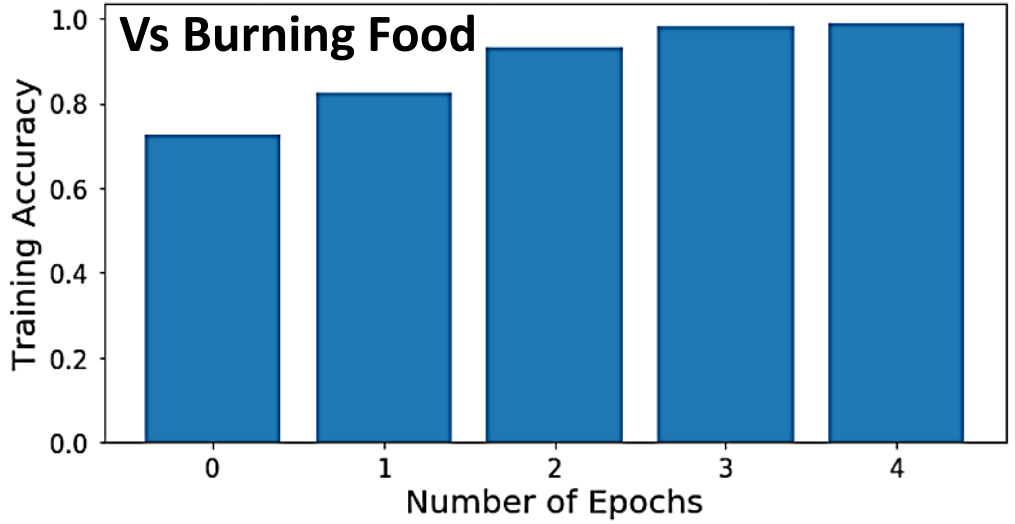




Training Accuracy for Cigarette Vs Vape



Training Accuracy for Cigarette/Vape Vs Burning Food



Hardware Architecture for Sensing at Scale

- Widespread application of sensing – across a Hospital, School, Workplace require hundreds/thousands of sensor nodes
- Users of these spaces need to know
  - (i) Toxicity levels tolerable for different spaces,
  - (ii)Flammability levels of different spaces
  - (iii)Concurrent Detection of any of several toxic/flammable emissions and their levels of toxicity/flammability in real time across the entire building/complex
- Cannot communicate data from sensors to Cloud – data privacy, latency may impose constraints
- Communicate Sensor data to AI platform within building/complex for training, inference
- Model size of sensor data modest (compared to full motion video data sets from several hundred cameras)
- Low cost AI hardware – NVDA AGX for example, can support concurrent processing of workload from all sensor nodes within building/complex

Conclusions & Summary

- We demonstrate with prototype hardware for the first time industry-wide, detection of cigarette emissions in particular and any toxic gas in general using pattern recognition with Machine Learning
- Our hardware and methods are over 10x faster, can detect a single cigarette consistently in less than 300 seconds from lighting a cigarette in large spaces where toxic gas concentrations are extremely low, undetectable with conventional technologies
- Our hardware and methods are consistent and reliable - do not lead to false alarms enabling fast detection at scale in buildings, industrial complexes of hospitals, schools, workplaces, hotels for the first time
- Our hardware and methods also enable classification of different levels of toxicity and flammability of any toxic gas produced/present in Hospitals, Industrial environments, Workplaces etc.

Acknowledgements

- Mentors at **Danbury High School** and our AP Physics Teachers:
  - Mr Jameson Parker & Mr David Honeyford
- Our Guidance Counselor and Principal:
  - Ms Amy Alonzi & Mr Daniel Donovan
- Mentor at **NJIT**:
  - Professor Hieu Nguyen, ECE

Our Startup – Exasense Technologies Corp

- **Vision:** Technologies enabling Intelligent Sensing at Scale
- **Founders:** Ibrahim & Adam Bhavnagarwala
- www.exasensetech.com (under construction)
- **IP Business Model** – supported by Proof of Concept, (multiple) US Patents (pending)
- We welcome **Industry Partners** to work with us to bring our IP to market