Ultrafine particle emissions from desktop 3D printers

NSF Workshop:
Environmental Implications of Additive Manufacturing
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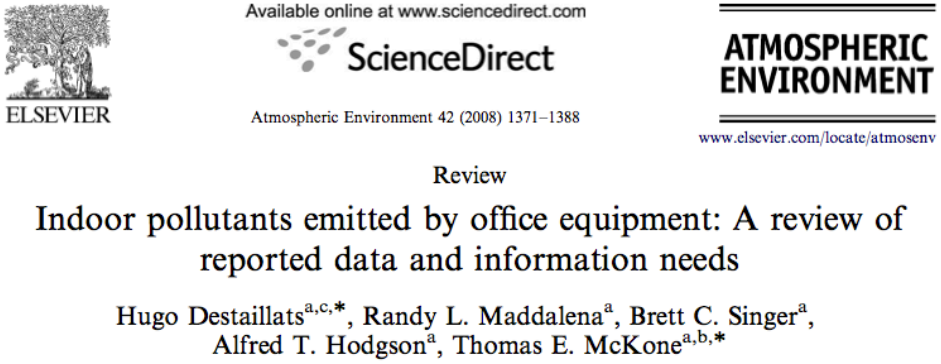
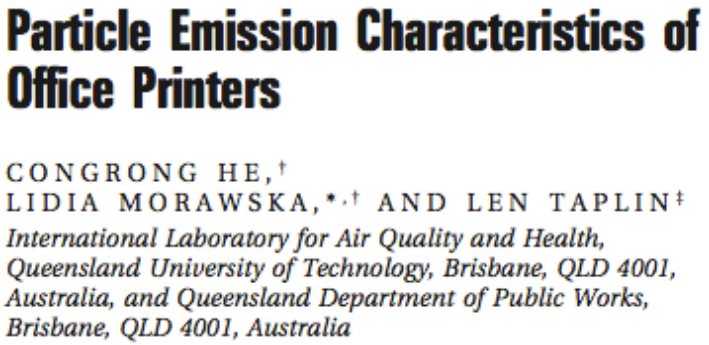
Potential for emissions from desktop 3D printers

- Why would we hypothesize that 3D printers emit pollutants?
  - Previous literature on office equipment and other indoor emitters
  - Knowledge of additive manufacturing (AM) processes
- Emissions from office equipment
  - Computers, printers, copy machines, and other common electronic equipment emit various pollutants
    - Volatile organic compounds (VOCs), semi-volatile organic compounds (SVOCs), ozone, and particulate matter (including ultrafine particles)



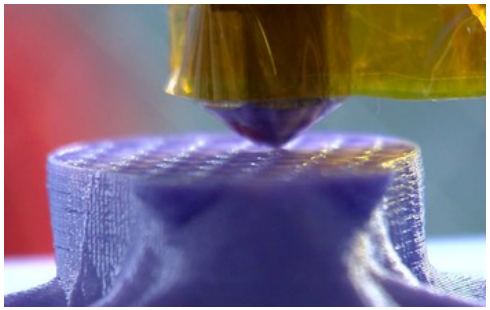
Destaillats et al. **2008** *Atmos Environ* 42:1371-1388

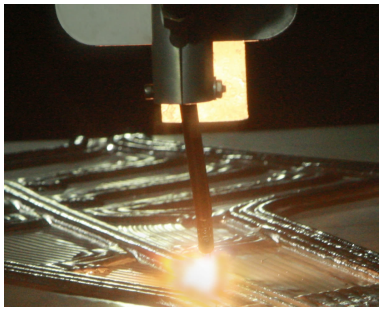


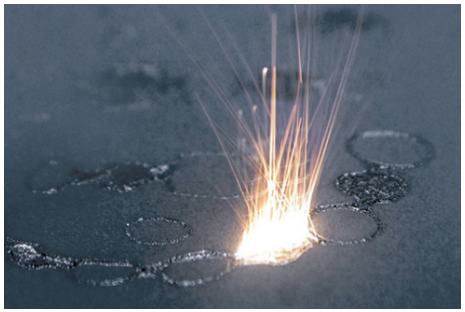
He et al. **2007** *Environ Sci Technol* 41:6039-6045

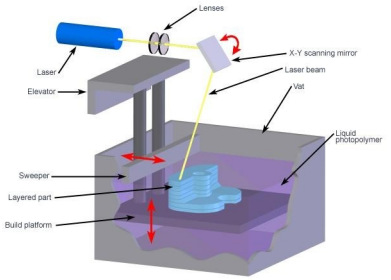
Potential for emissions from desktop 3D printers

- Types of 3D printing / AM processes:
  - Extrusion (fused deposition modeling, molten polymer deposition)
  - Wire (electron beam freeform fabrication)
  - Granular (laser sintering / melting)
  - Powder bed (plaster)
  - Laminated object manufacturing
  - Light polymerization (stereo lithography / digital light processing)
- Many of these processes involve high temperatures, melting, and sintering that are likely to (or have been shown to) emit various pollutants









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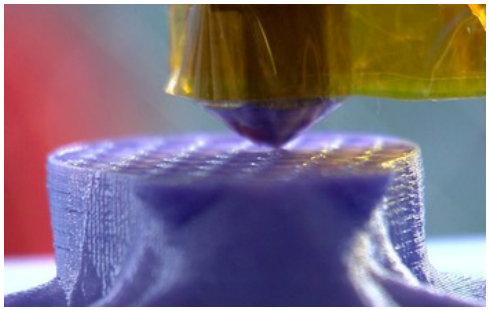
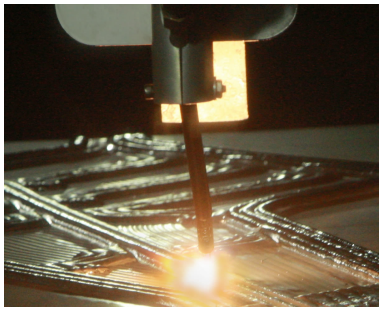
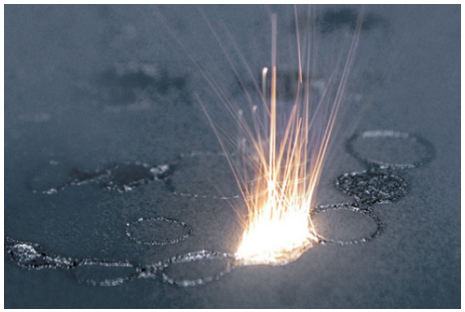
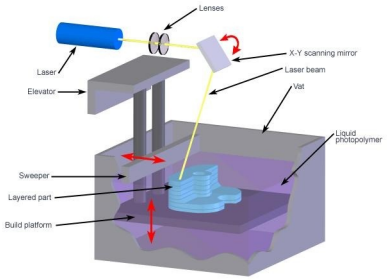






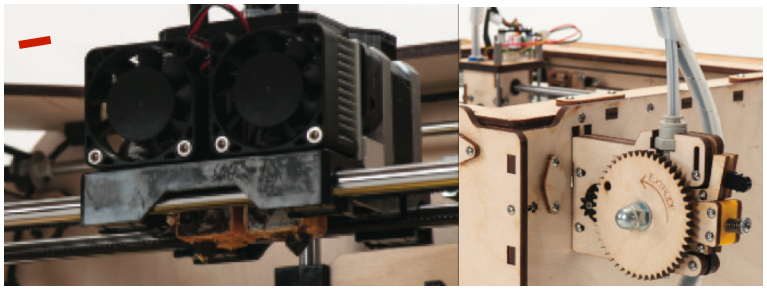


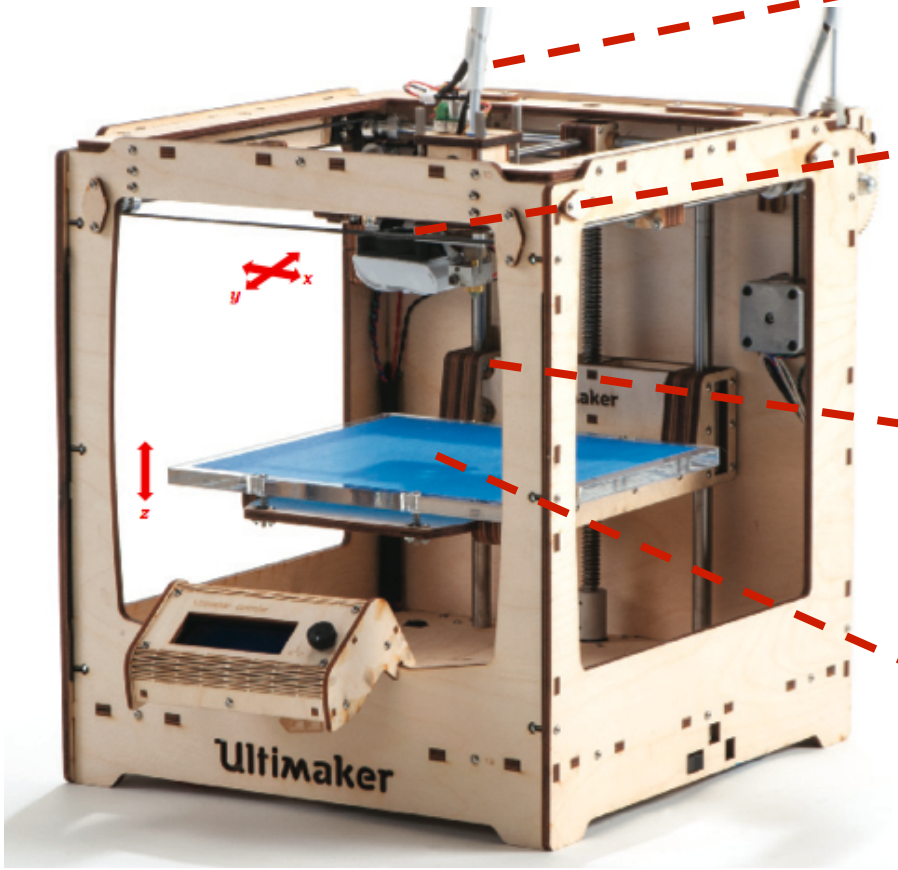
Additive 3D printers: Extrusion (MPD/FDM)

Most desktop 3D printers use a technique called **molten polymer deposition (MPD)**, or **fused deposition modeling (FDM)**

Thermoplastic filament

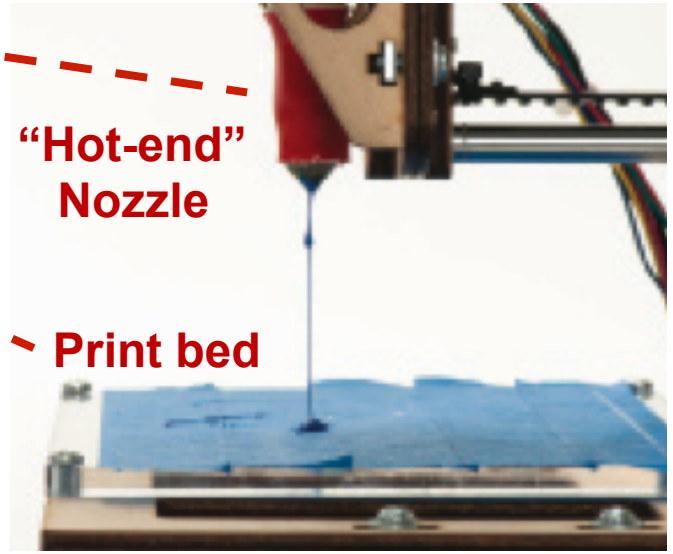
Extruder



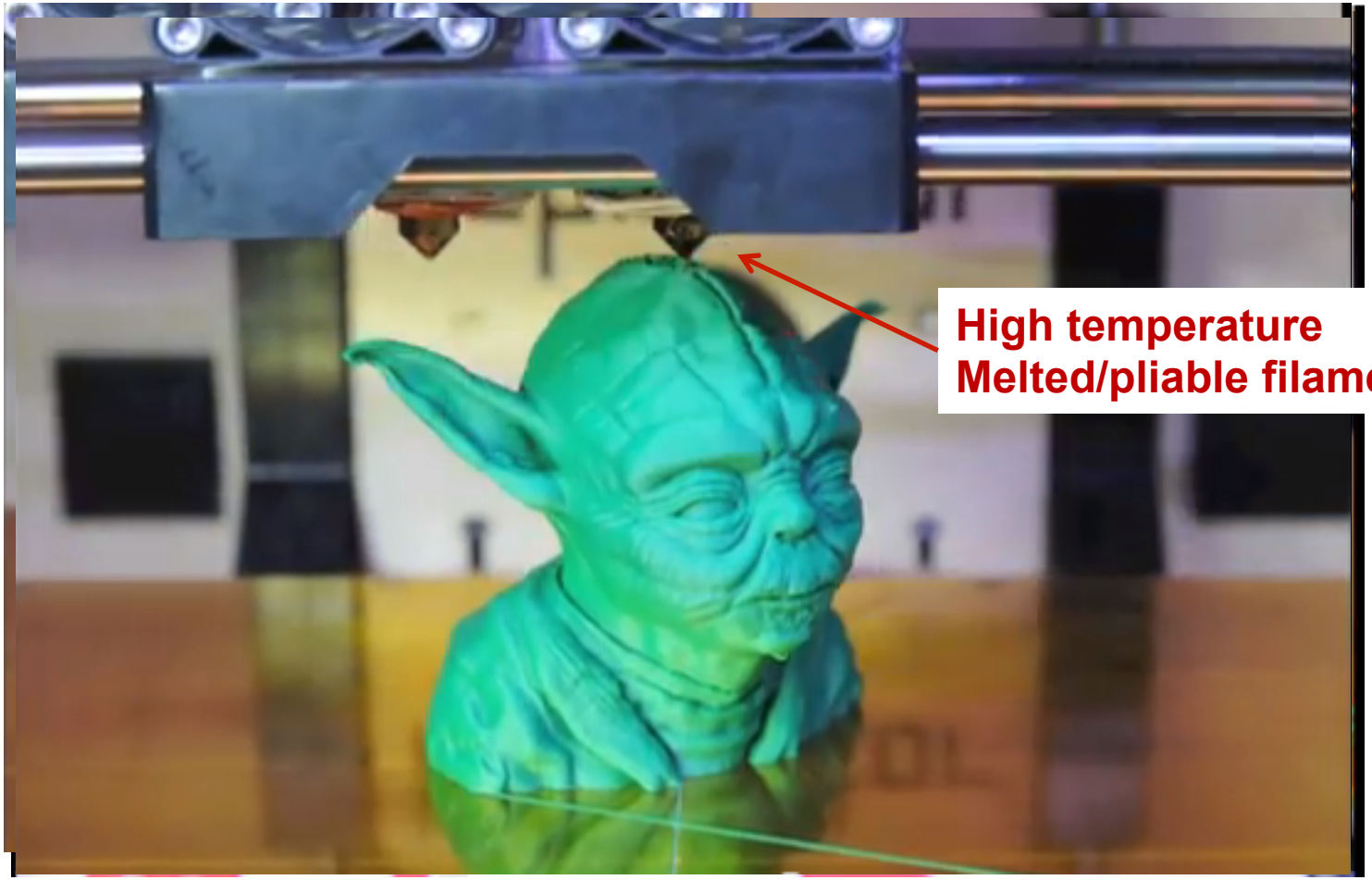


"Hot-end" Nozzle

Print bed



MPD/FDM 3D printer in action



Yoda head @ 0.1 mm layer height | http://www.youtube.com/watch?v=8_vloWVgf0o

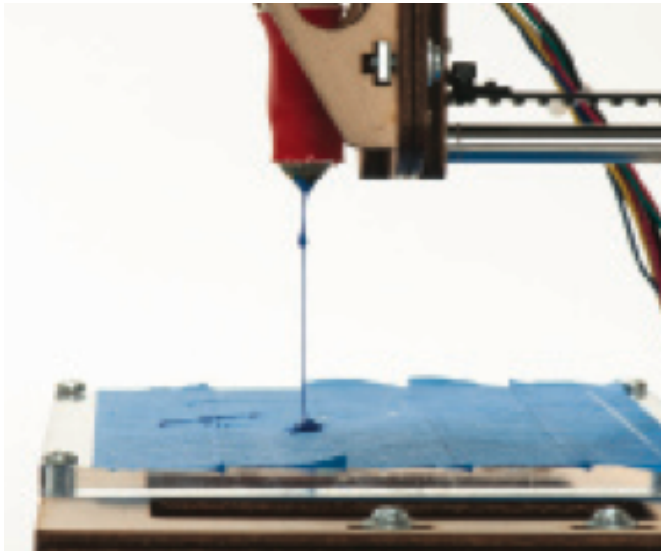
Additive 3D printers: MPD/FDM

Thermoplastic filaments

Acrylonitrile butadiene styrene (ABS)
Polylactic acid (PLA)
Polyvinyl alcohol (PVA)
Many others

Hot-end nozzle

0.2-0.8 mm diameter hole
~215-250°C for ABS
~160-220°C for PLA
~190°C for PVA



Print bed

~110°C for ABS
<40°C for PLA

Thermoplastic extrusion/deposition: Cause for concern?

- Previous work on large scale industrial thermoplastic processing showed that both gases and particles are emitted during operation

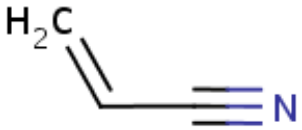
  Rutkowski and Levin **1986** *Fire and Materials* 10:93-105; Contos et al. **1995** *J Air Waste Manag Assoc* 45:686-694; Unwin et al. **2013** *Ann Occ Hygiene* 57(3):399-406

- Exposure to decomposition products from **ABS** thermal processing has been shown to have toxic effects in rats and mice

  Zitting and Savolainen **1980** *Archives of Toxicology* 46:295-304; Schaper et al. **1994** *Am Indust Hyg Assoc J* 55:924-934

ACRYLONITRILE

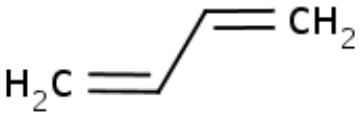
CASRN: 107-13-1



IARC Group 2B: Possibly a Human Carcinogen

1,3-BUTADIENE

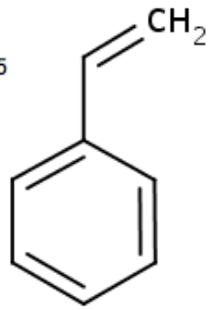
CASRN: 106-99-0



IARC Group 1: Carcinogenic to Humans

STYRENE

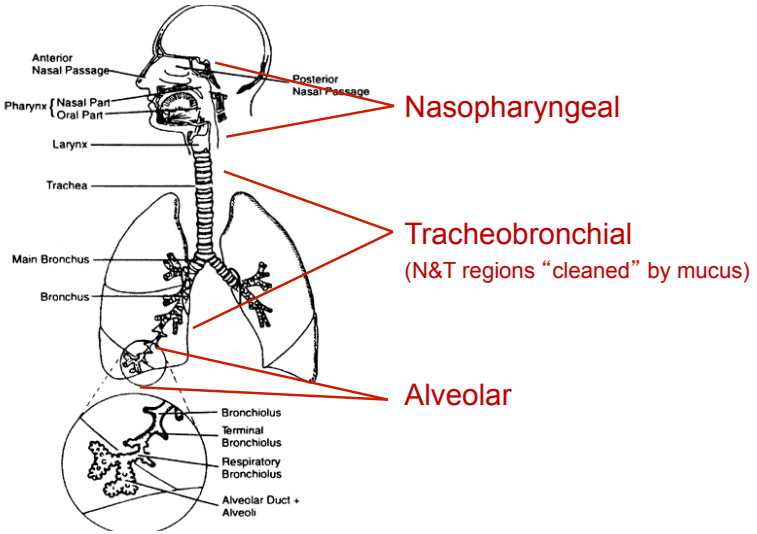
CASRN: 100-42-5

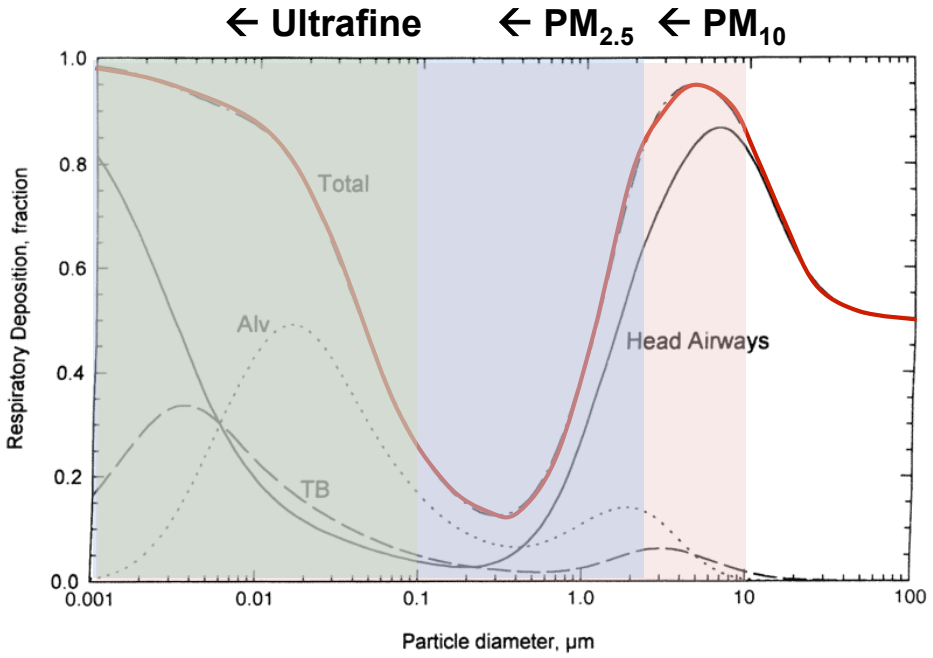


IARC Group 2B: Possibly a Human Carcinogen

Thermoplastic extrusion/deposition: Cause for concern?

- Exposure to fumes from thermal decomposition of other plastics (e.g. PTFE) has been shown to be acutely toxic to mammals Oberdörster et al. **2005** *Environ Health Persp* 113:823-839
  - Ultrafine particles appear to be more toxic than gases Oberdörster et al. **1995** *Inhal Toxicol* 7:111-124; Johnston et al. **2000** *Toxicol Applied Pharmacol* 168:208-215
- Ultrafine particles (particles <100 nm in size)



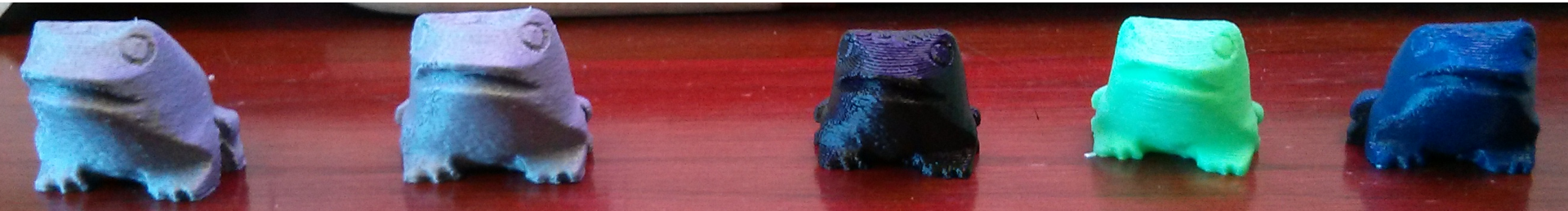


Our ad-hoc experiment

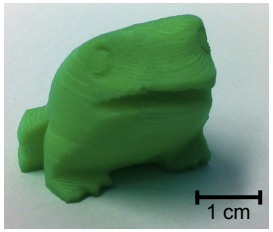
- Five 3D printers were tested
  - All 5 were the same popular commercial variety
  - All *unenclosed* designs

Stephens et al. **2013** *Atmos Environ* 79:334-339

- Two types of filaments at different operational conditions
  - 2 PLA @ 200°C nozzle and 18°C bed temperatures
  - 3 ABS @ 220°C nozzle and 118° bed temperatures
- Operating in a closed 45 m^3 (1600 ft^3) office environment
  - Floor area ~19 m^2 (200 ft^2)
- Ultrafine particle concentrations measured w/ TSI NanoScan SMPS Tritscher et al. **2013** *J Physics* 429

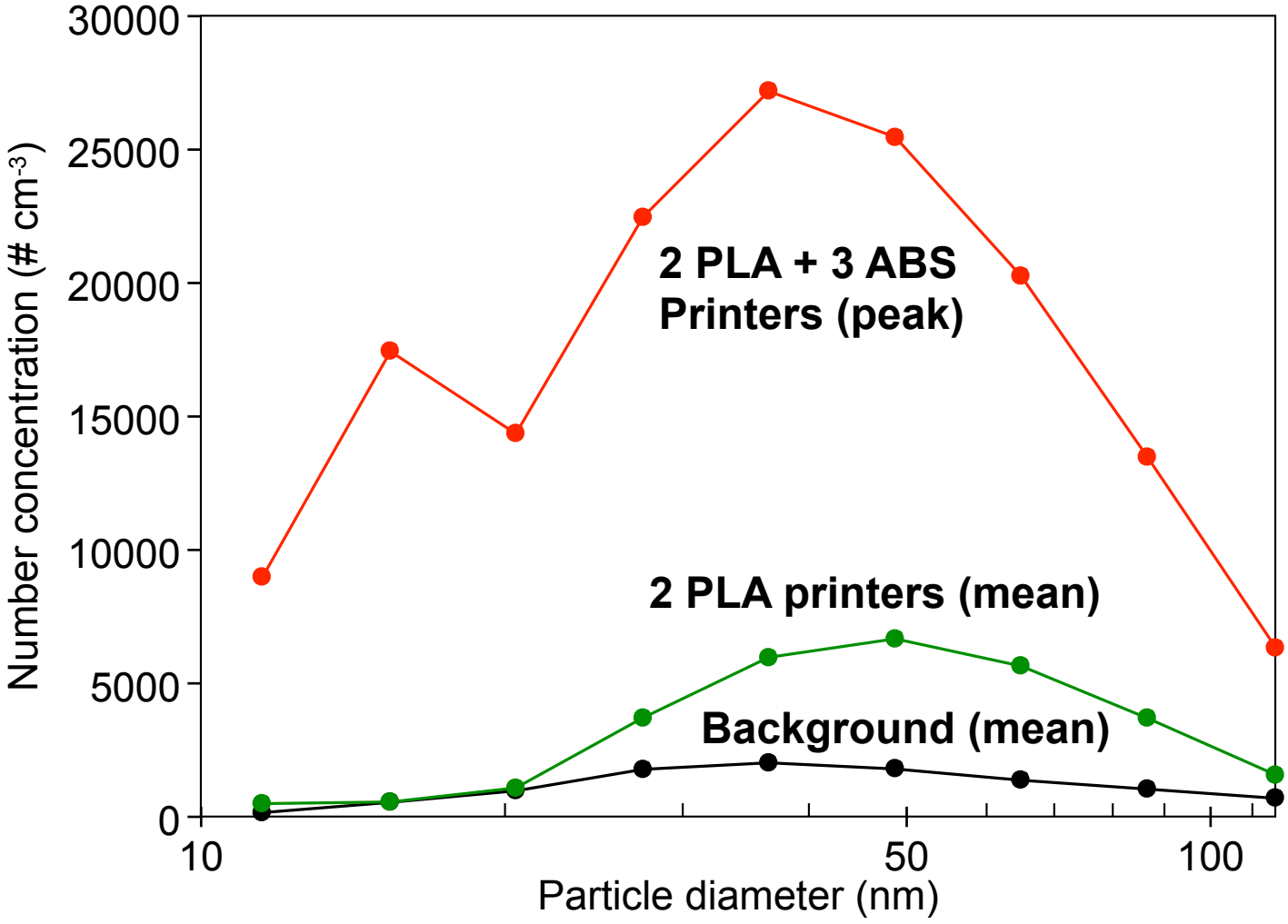


Measured ultrafine particle concentrations



Stephens et al. **2013** *Atmos Environ* 79:334-339

Mean and peak UFP size distributions



Total UFP summary
2 PLA + 3 ABS peak:
~142,000 #/cm^3

This UFP exposure is higher than you'll see within 300 feet of major highways

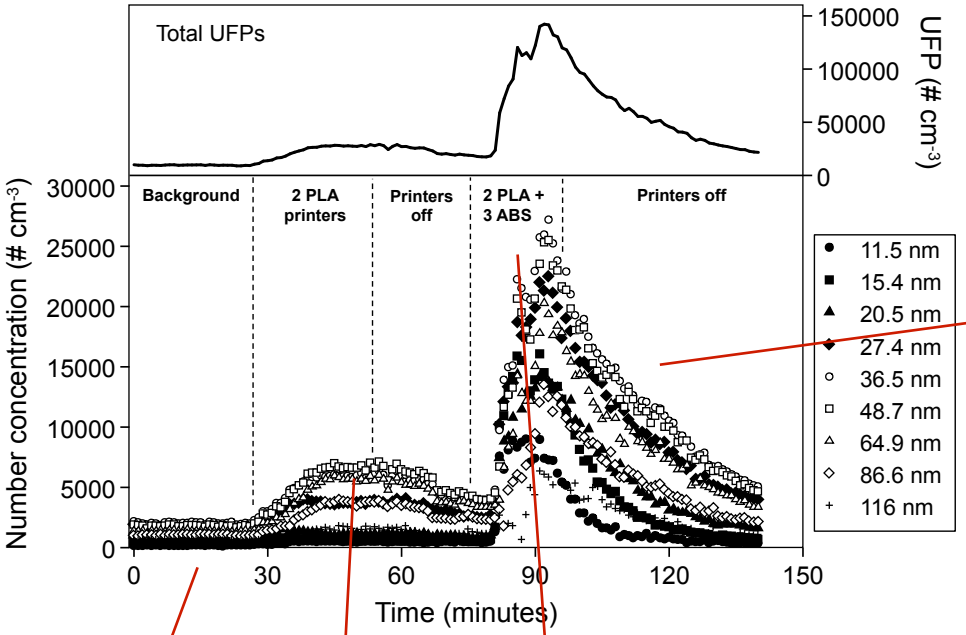
Zhu et al. **2002** *Atmos Env*
Fuller et al. **2012** *Atmos Env*

2 PLA mean:
~28,000 #/cm^3

Background mean:
~10,000 #/cm^3

Stephens et al. **2013** *Atmos Environ* 79:334-339

Estimating emission rates



Emission rates are independent of the test space

$$\ln\left(\frac{C_{i,in}(t)-C_{i,in,ss,bg}}{C_{i,in}(t=0)-C_{i,in,ss,bg}}\right)=-L_i t$$

Units

C_i	[#/cm^3]
E_i	[#/min]
L_i	[1/min]
V	[cm^3]

$C_{i,in,ss,bg}$

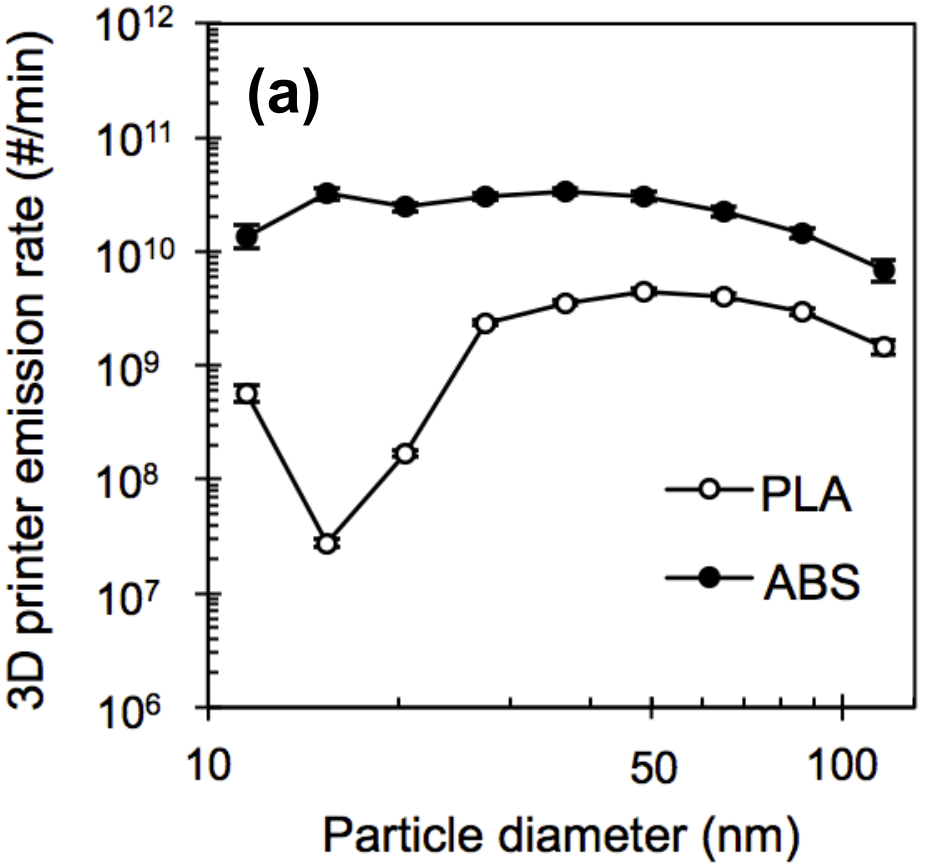
$$C_{i,in,ss,2PLA}=C_{i,in,ss,bg}+\frac{2\left(E_{i,PLA}/V\right)}{L_i}$$

$$C_{i,in}\left(t\right)=C_{i,in,t=0}e^{-L_i t}+\left[C_{i,in,ss,bg}+\frac{2\left(E_{i,PLA}/V\right)+3\left(E_{i,ABS}/V\right)}{L_i}\right]\left(1-e^{-L_i t}\right)$$

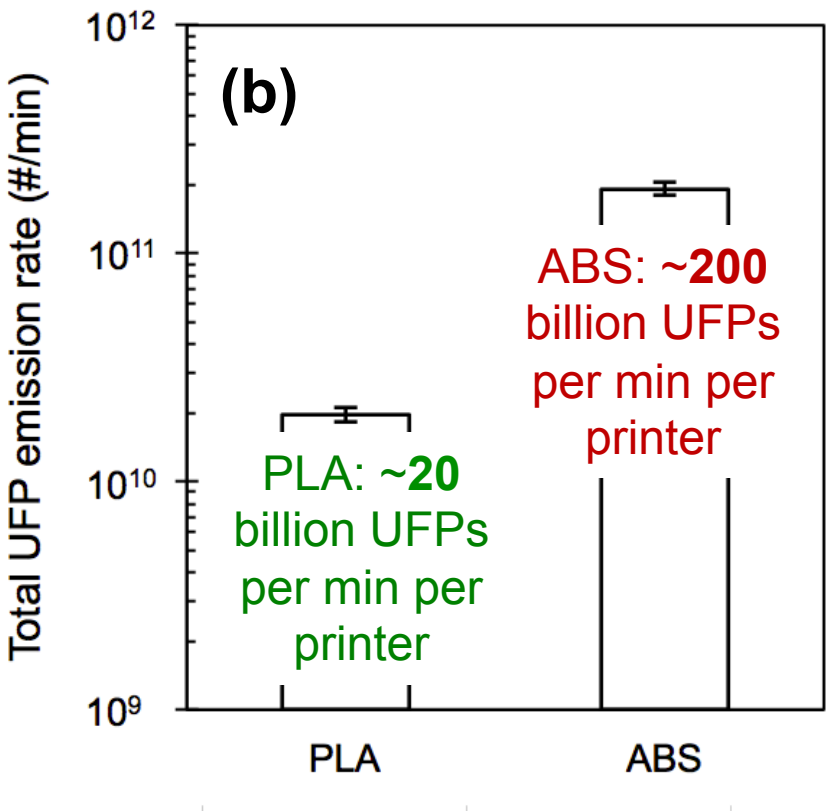
Stephens et al. **2013** *Atmos Environ* 79:334-339

Size-resolved and total UFP emission rates

Size-resolved UFP emission rates



Total UFP emission rates



Total UFP emission rates:

~1.9×10^{11} #/min from ABS printer

~2.0×10^{10} #/min from PLA printer

Stephens et al. **2013** *Atmos Environ* 79:334-339

Comparison of emission rates to other indoor emitters

Comparison of total UFP emission rates:

UFP emitting device	Size range	Emission rate (#/min)	Reference
Flat iron with steam	20-1000 nm	6.0×10^{9}	Afshari et al. (2005)
Electric frying pan	10-400 nm	$1.1\text{-}2.7\times10^{10}$	Buonnano et al. (2009)
PLA	10-100 nm	$\sim2.0\times10^{10}$	*This study*
Vacuum cleaner	20-1000 nm	3.5×10^{10}	Afshari et al. (2005)
Scented candles	20-1000 nm	8.8×10^{10}	Afshari et al. (2005)
Gas stove	20-1000 nm	1.3×10^{11}	Afshari et al. (2005)
ABS	10-100 nm	$\sim1.9\times10^{11}$	*This study*
Cigarette	20-1000 nm	3.8×10^{11}	Afshari et al. (2005)
Electric stove	20-1000 nm	6.8×10^{11}	Afshari et al. (2005)
Frying meat	20-1000 nm	8.3×10^{11}	Afshari et al. (2005)
Radiator	20-1000 nm	8.9×10^{11}	Afshari et al. (2005)
Laser printers	6-3000 nm	4.3×10^{9} to 3.3×10^{12}	He et al. (2010)
Cooking on a gas stove	10-400 nm	$1.1\text{-}3.4\times10^{12}$	Buonnano et al. (2009)

What we do **not** know:

- Impacts of composition on toxicity
- Impacts of realistic exposures on potential health outcomes

Potential health implications

- UFPs deposit efficiently in the alveolar regions of the lung
- Deposition in head airways can lead to translocation to the brain via the olfactory nerve Hinds **1999** *Aerosol Technol*; Chalupa et al. **2004** *EHP* 112:879-882 Oberdörster et al., **2004** Inhal Toxicol 16:437-445
- High surface areas of UFPs → high concentrations of adsorbed/condensed compounds Delfino et al., **2005** *EHP* 113:934-946; Sioutas et al., **2005** *EHP* 113:947-955
- Elevated UFP number concentrations are associated with adverse health effects in epidemiological studies
  - Total and cardio-respiratory mortality Stölzel et al., **2007** *JESEE* 17:458-467
  - Hospital admissions for stroke Andersen et al., **2010** *Eur Heart J* 31:2034-2040
  - Asthma symptoms Peters et al., **1997** *Am J Resp Crit Car Med* 155:1376-1383; Penttinen et al., **2001** *Eur Resp J* 17:428-435; Von Klot et al., **2002** *Eur Resp J* 20:691-702
- Composition: ABS byproducts are known to be toxic
  - PLA is actually known for its biocompatibility (but its byproducts?)

    Anderson and Shive **1997** *Adv Drug Delivery Rev* 28:5-24;
    Hans and Lowman **2002** *Current Opinion in Solid State and Materials* Sci 6:319-327

Recent health implications: Other indoor sources of UFPs

Effects of copy center particles on the lungs: a toxicological characterization using a *Balb/c* mouse model

Sandra Pirela[1], Ramon Molina[1], Christa Watson[1], Joel M. Cohen[1], Dhimiter Bello[1,2], Philip Demokritou[1], and Joseph Brain[1]

[1]Center for Nanotechnology and Nanotoxicology, Department of Environmental Health, Harvard School of Public Health, Boston, MA, USA, and [2]Work Environment, Nanomanufacturing Center for Excellence, Biomedical Engineering & Biotechnology Program, University of Massachusetts, Lowell, MA, USA

"Our results indicate that exposure to copier-emitted nanoparticles may induce lung injury and inflammation."

Pirela et al., **2013** *Inhal Toxicol* 25:498-508

Nanoparticles from photocopiers induce oxidative stress and upper respiratory tract inflammation in healthy volunteers

Madhu Khatri[1,2], Dhimiter Bello[1], Peter Gaines[2], John Martin[1], Anoop K Pal[1], Rebecca Gore[1] & Susan Woskie[1]

[1]Department of Work Environment, University of Massachusetts-Lowell, Lowell, MA, USA and [2]Department of Biological Sciences, University of Massachusetts Lowell, Lowell, MA, USA

"We conclude that NPs from photocopiers induce upper airway inflammation and oxidative stress."

Khatri et al., **2013** *Nanotoxicology* 7:1014-1027

News coverage: Tell your own story

FOX NEWS .com Fair & Balanced

Are 3D printers harmful to your health?

BETA D NEWS

GEAR AND GADGETS

3-D Printers Might Be Hazardous To Your Health

JUL 25, 2013 03:34 PM ET // BY JESSE EMSPAK

Airborne particles from 3D printers could be as harmful to your health as cigarette smoke

Mail Online

The Telegraph 3D printers could cause strokes, researchers warn

FAST COMPANY

Will A 3-D Printer Destroy Your Lungs?

Is There Long-Term Health Risks to 3-D Printing? One Study Says 'Yes'

StreetInsider.com

if you're not inside...you're outside

Public and scientific interest

Atmospheric Environment

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1. Ultrafine particle emissions from desktop 3D printers

November 2013

Brent Stephens | Parham Azimi | Zeineb El Orch | Tiffanie Ramos

The development of low-cost desktop versions of three-dimensional (3D) printers has made these devices widely accessible for rapid prototyping and small-scale manufacturing in home and office settings....

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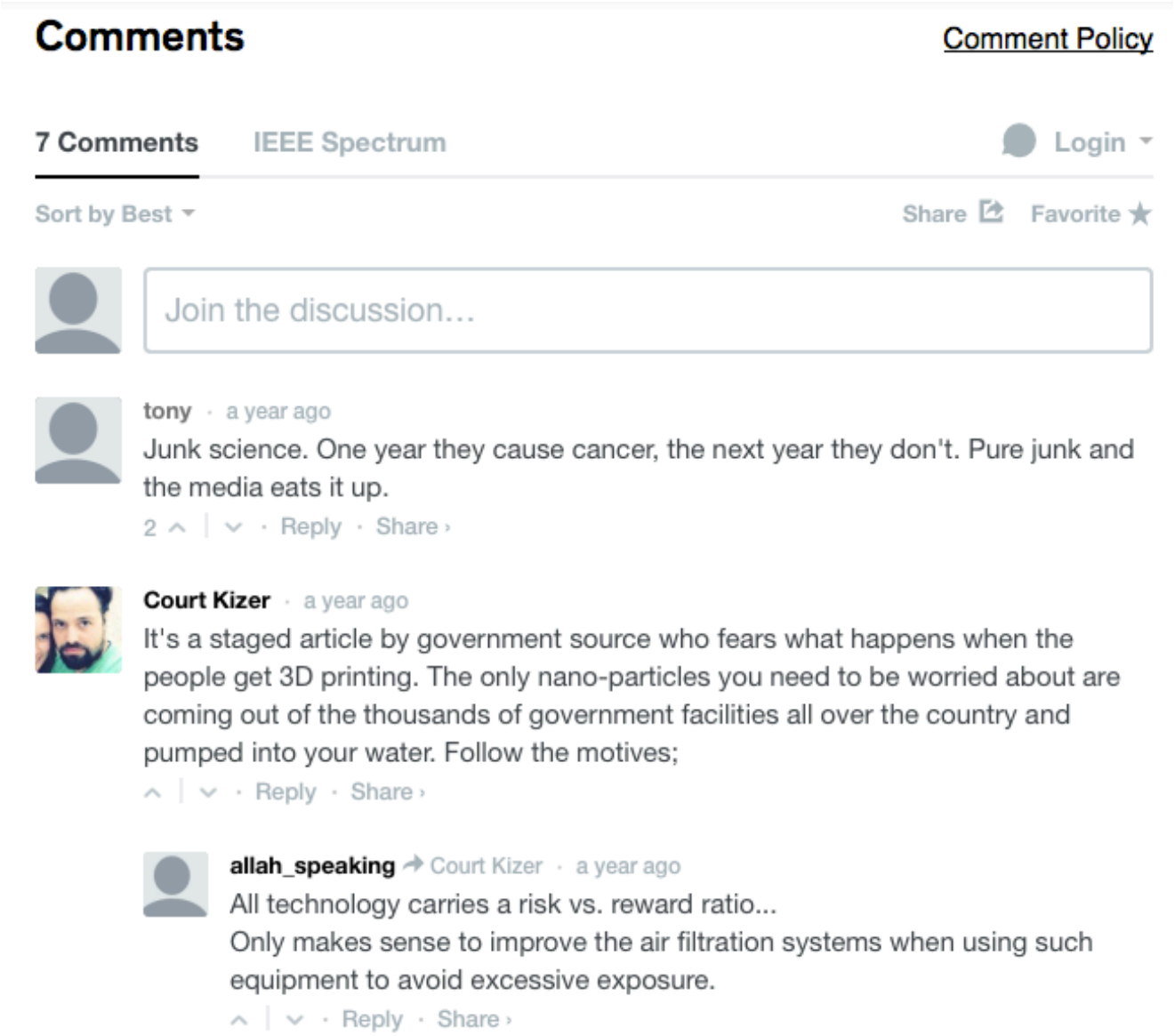
Accessed October 7, 2014

Public interest/skepticism



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Join the discussion…

tony · a year ago

Junk science. One year they cause cancer, the next year they don't. Pure junk and the media eats it up.

2 · Reply · Share ›

Court Kizer · a year ago

It's a staged article by government source who fears what happens when the people get 3D printing. The only nano-particles you need to be worried about are coming out of the thousands of government facilities all over the country and pumped into your water. Follow the motives;

· Reply · Share ›

allah_speaking Court Kizer · a year ago

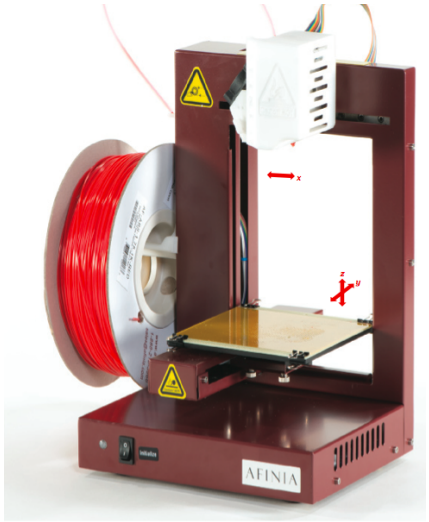
All technology carries a risk vs. reward ratio...
Only makes sense to improve the air filtration systems when using such equipment to avoid excessive exposure.

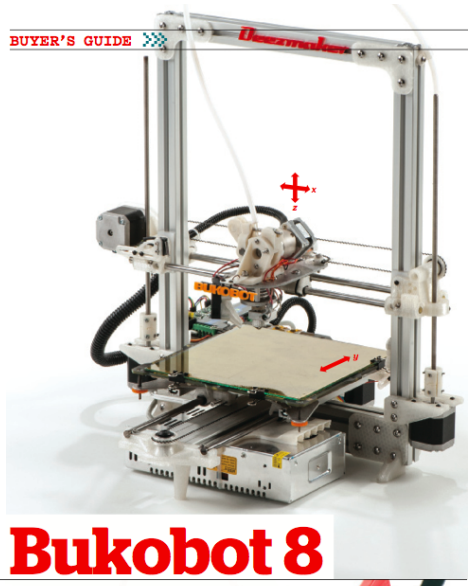
· Reply · Share ›

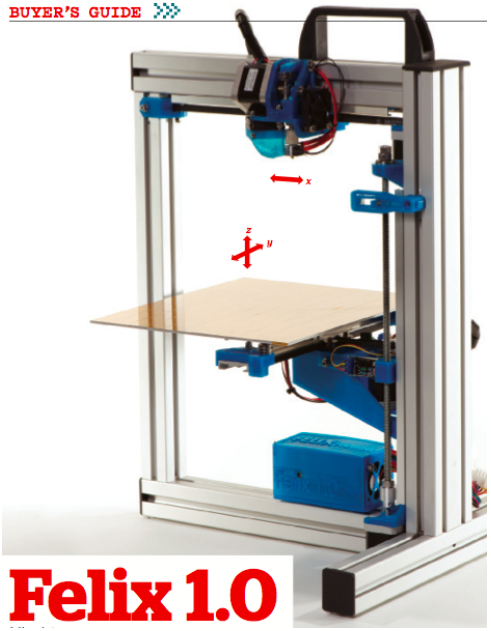
Moving forward: Research needs

1. Characterize **emissions**
   - More printers, more filaments, both particles (UFPs) and gas-phase compounds (VOCs, SVOCs), chemical constituents
2. Characterize **exposures** in realistic environments
   - Homes, offices, schools, etc.
3. Inhalation **toxicology** and **health** outcomes
   - Using cell lines, mouse models, or human subjects
4. Investigate **control strategies**
   - Exhaust ventilation, gas and particle filtration, enclosures

Could simple enclosures help?







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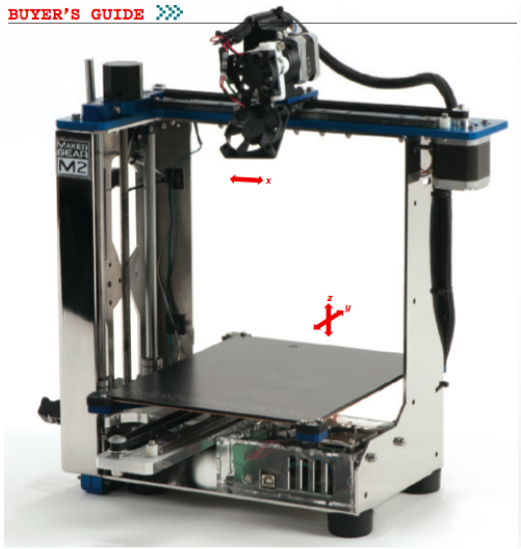
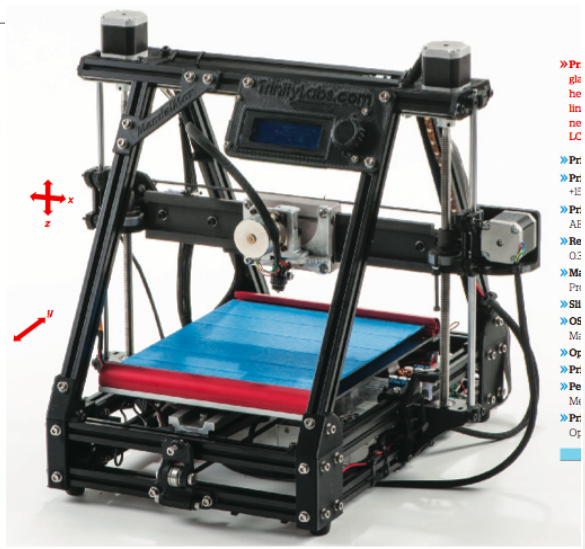
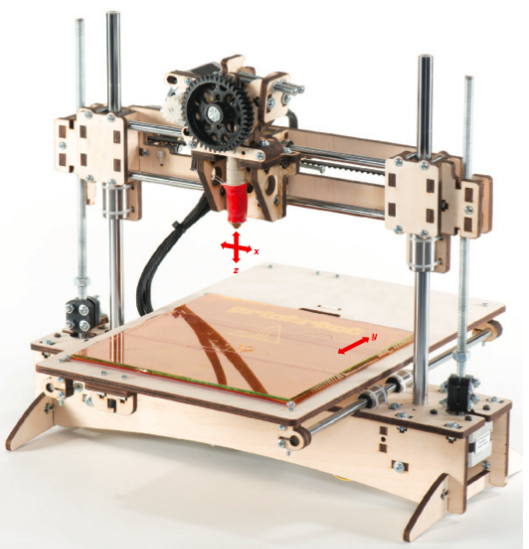


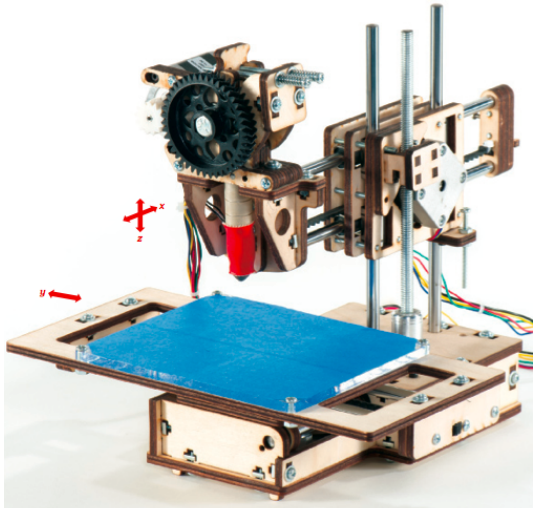
MakerGear M2



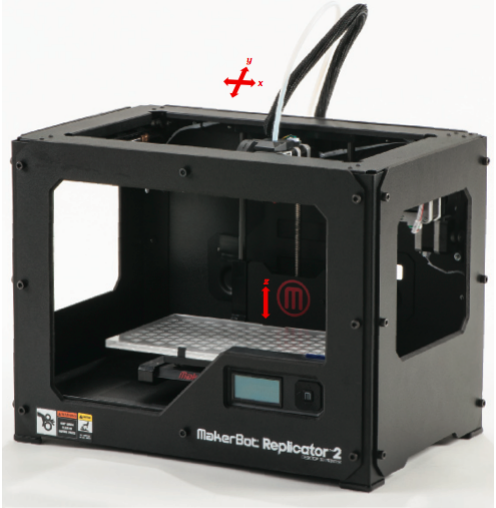
MendelMaxPro



Printrbot LC

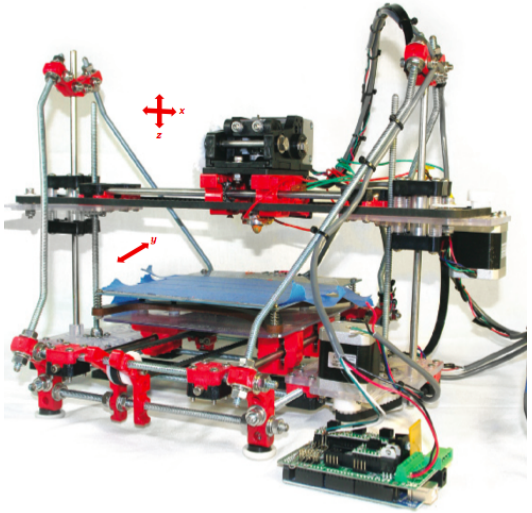


Printrbot Jr.



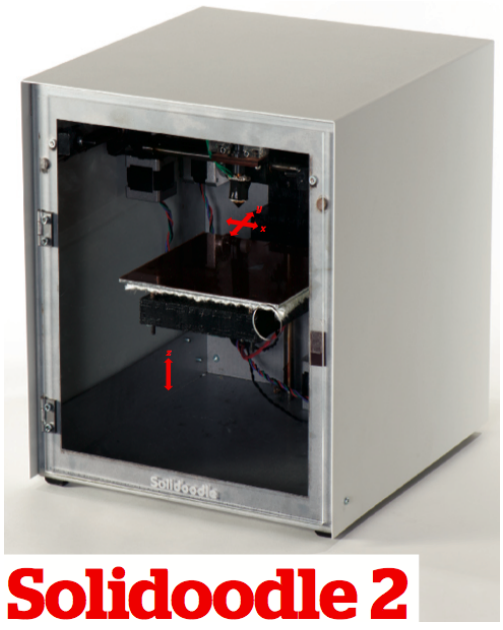
Replicator 2

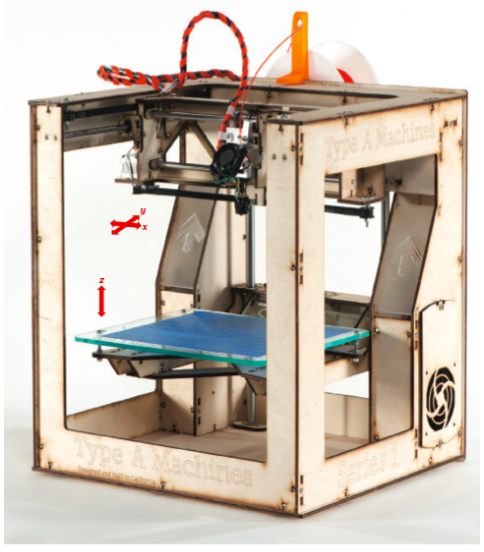
MakerBot Industries makerbot.com

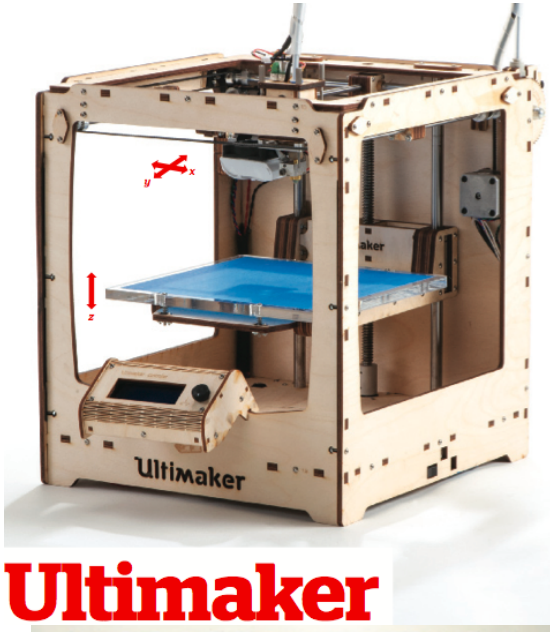


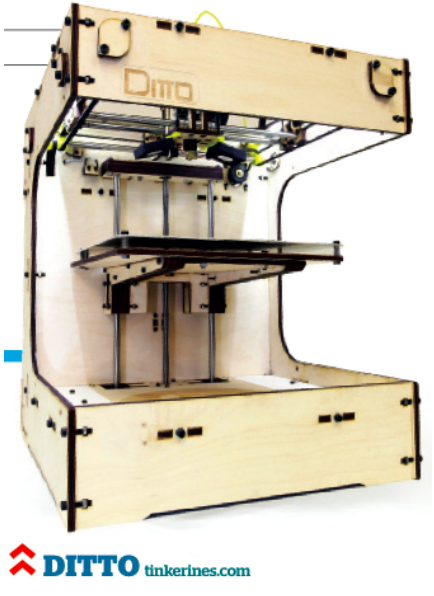
SeeMeCNC H1.1

Could simple enclosures help?

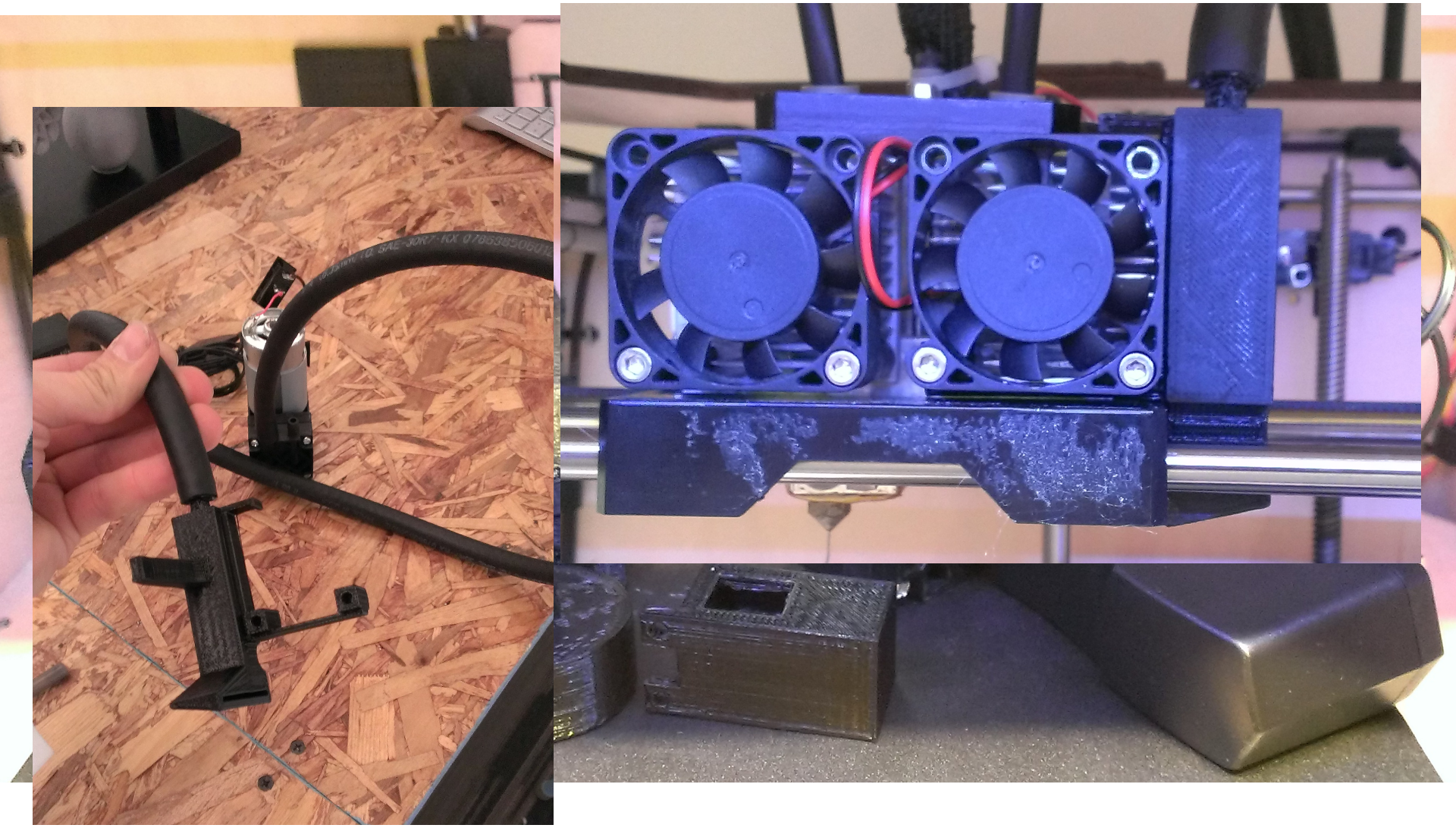








Potential for (3D printed) 3D printer filtration systems



Photos courtesy Mike Moceri, The 3D Printer Experience

New research funding announcement

We were recently awarded research funding through CDC:

- NIOSH R03: *Evaluating and controlling airborne emissions from desktop 3D printers*

Three phases over 2 years:

1. Chamber testing to characterize emissions of particles and VOCs from 5 of the most popular desktop 3D printers
2. Measurements (and models) of realistic exposures in real occupational environments
3. Development and evaluation of custom gas and particle filtration devices and enclosures

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  - Parham Azimi, Tiffanie Ramos, Zeineb El Orch, and Bobby Zylstra
- The 3D Printer Experience, Chicago, IL
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Questions/Comments

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