Ultrafine particle emissions from desktop 3D printers

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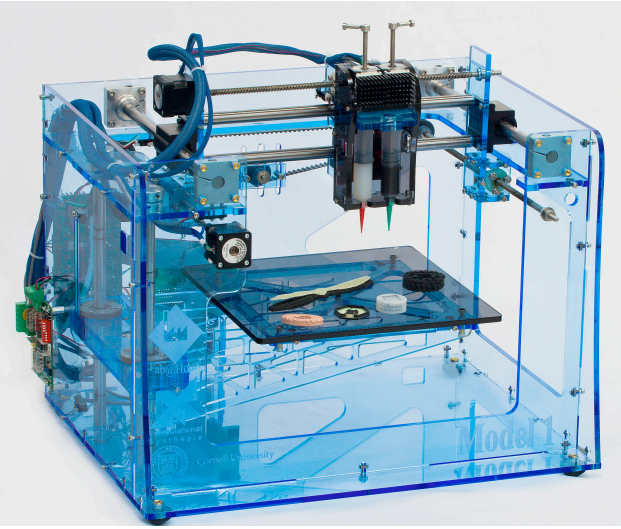
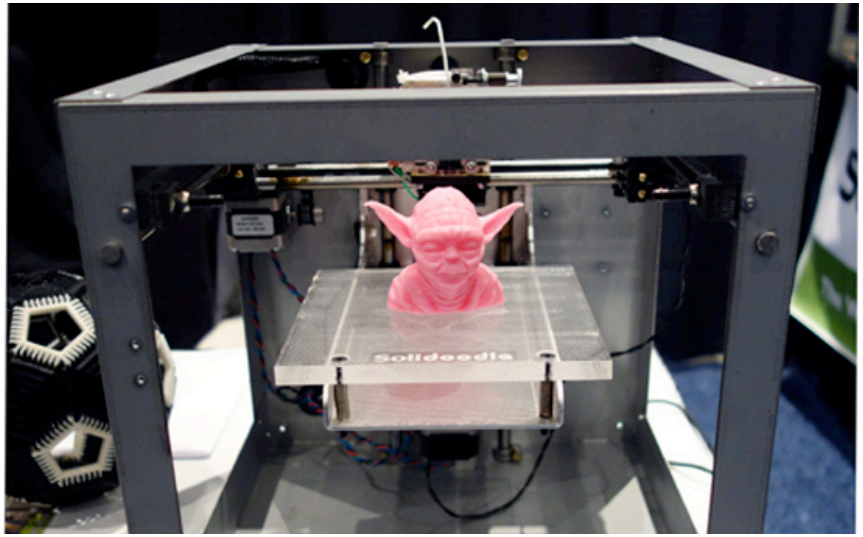
What is a 3D printer?

3D printing – or additive manufacturing – is a process of making a three-dimensional solid object from a digital model

- Widely used in rapid prototyping and custom fabrication
- Commercial applications include industrial design, architecture, engineering, fashion, dental industries, biotech, food, and many others



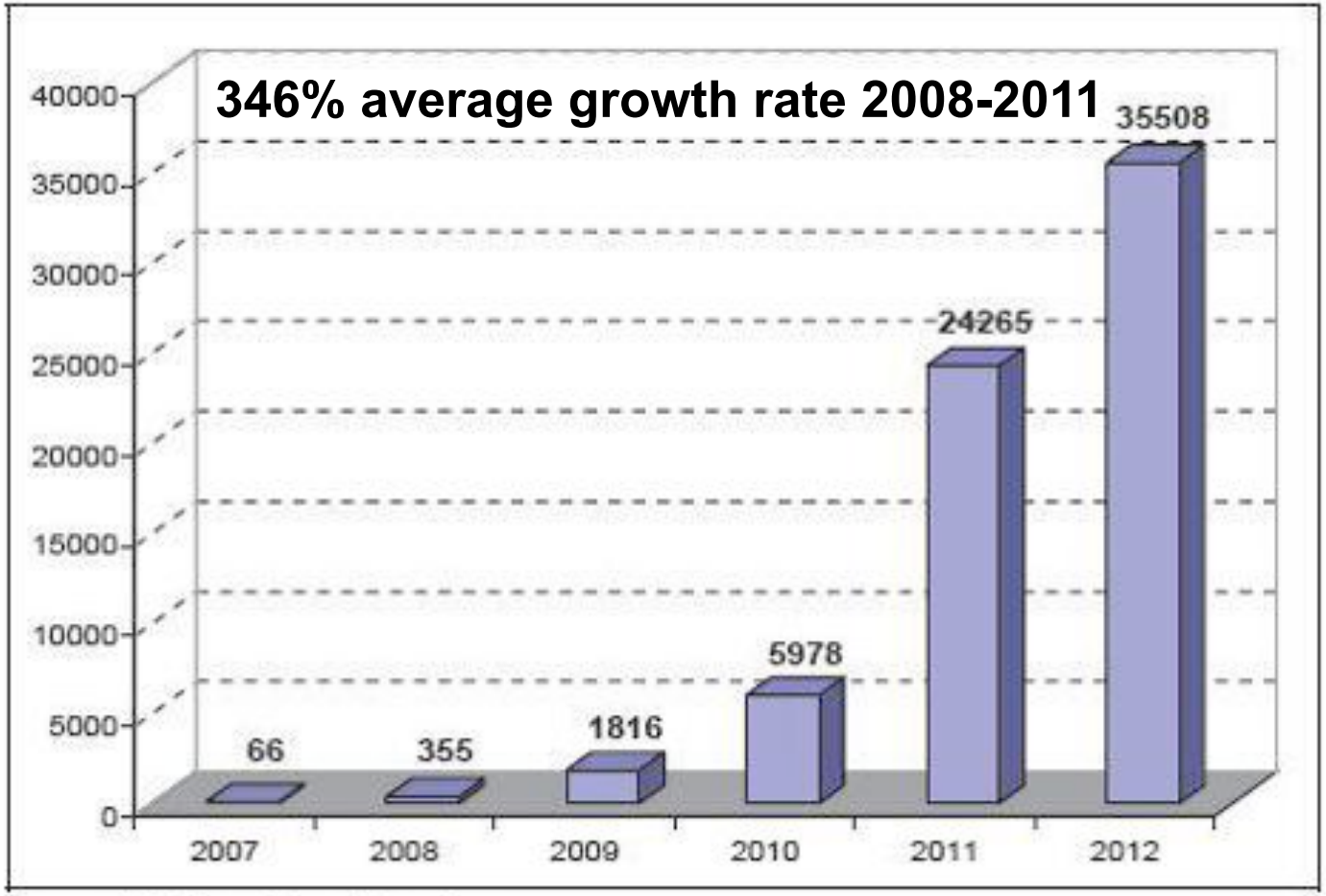


Recent advances have greatly reduced costs and made 3D printers widely available for less than $2,500 (or as little as $500)

For as little as $500…

You can make all this ~~junk~~ interesting stuff!

Personal 3D printer sales are rising steadily



Source: Wohlers Associates, Inc.

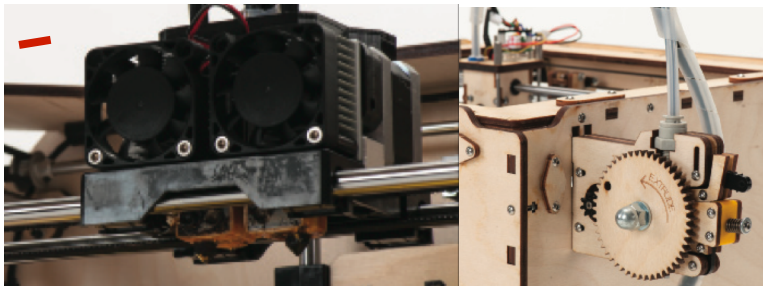
Approximately **70,000** personal 3D printers in circulation in 2012

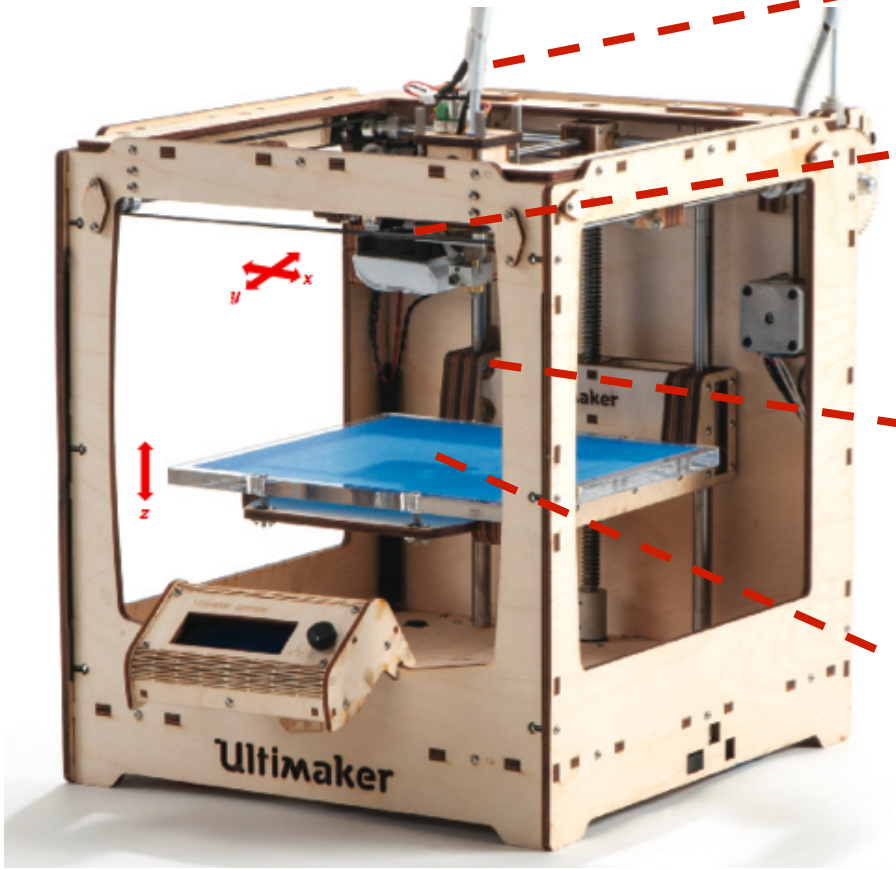
Additive 3D printers: MPD/FDM

Most 3D printers use a technique called **molten polymer deposition (MPD)**, also known as **fused deposition modeling (FDM)**

Thermoplastic filament

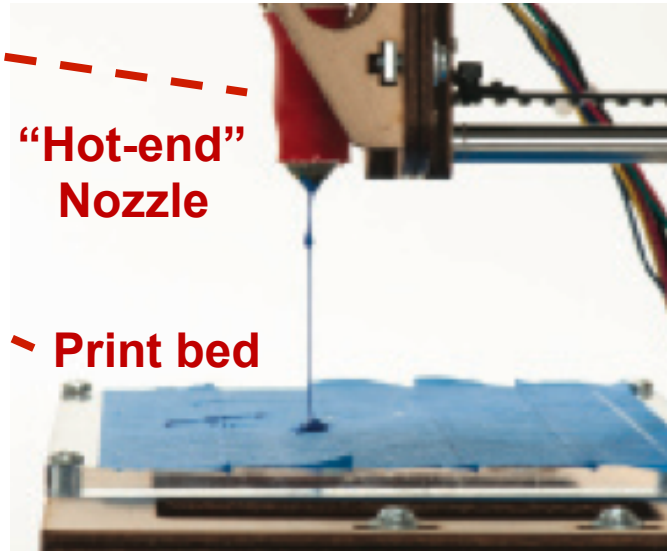
Extruder



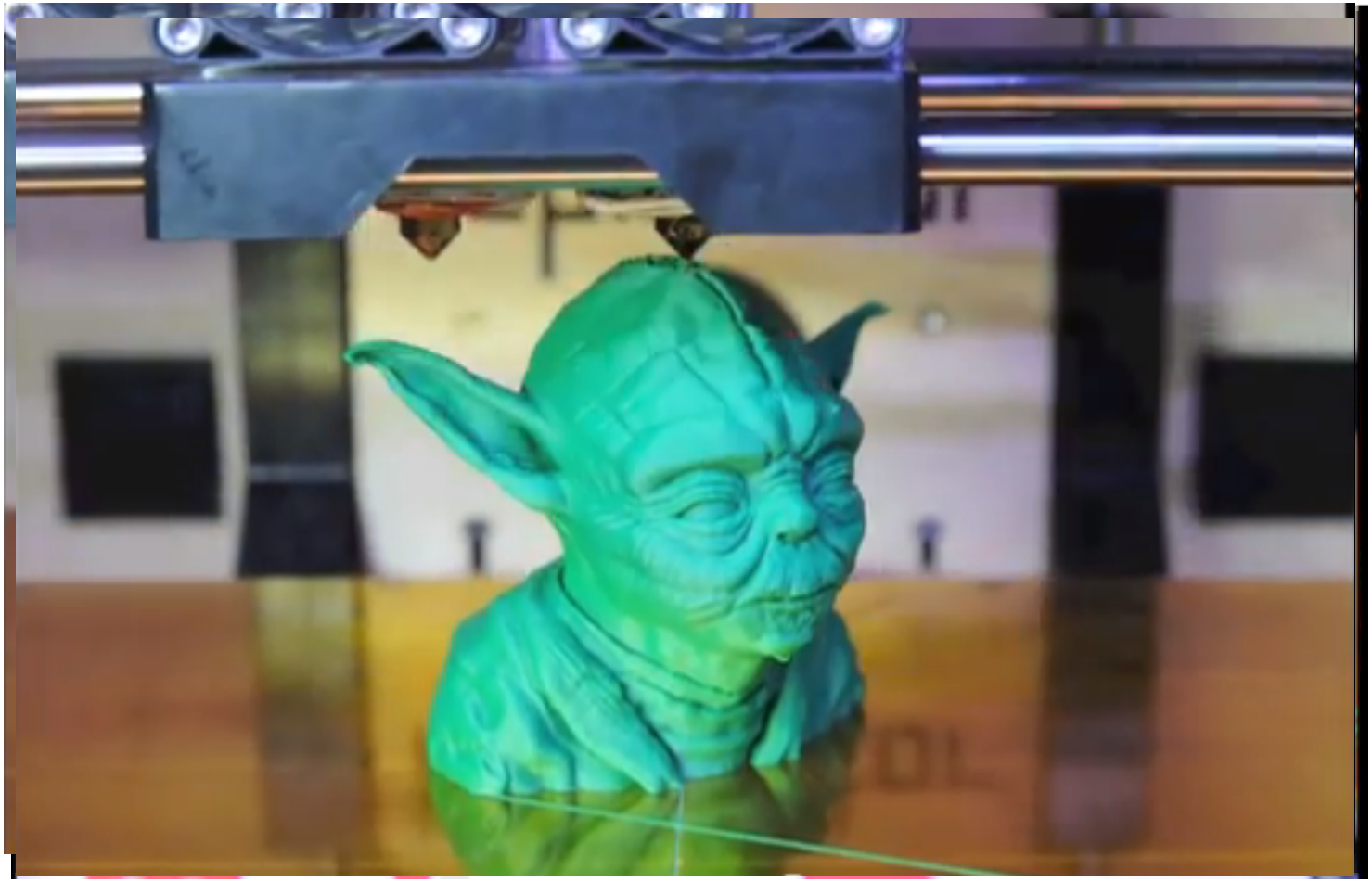


"Hot-end" Nozzle

Print bed



MPD/FDM 3D printer in action



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

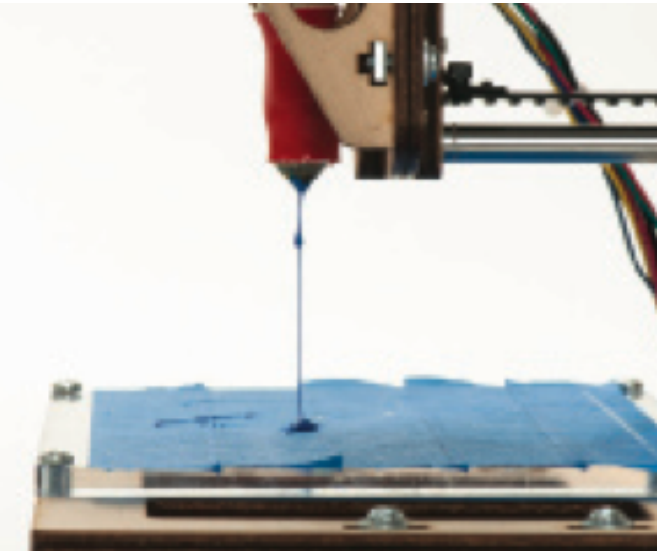
Additive 3D printers: MPD/FDM

Thermoplastic filaments

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

Hot-end nozzle

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



Print bed

<40°C for PLA
~110°C for ABS

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

- 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

Our ad-hoc experiment

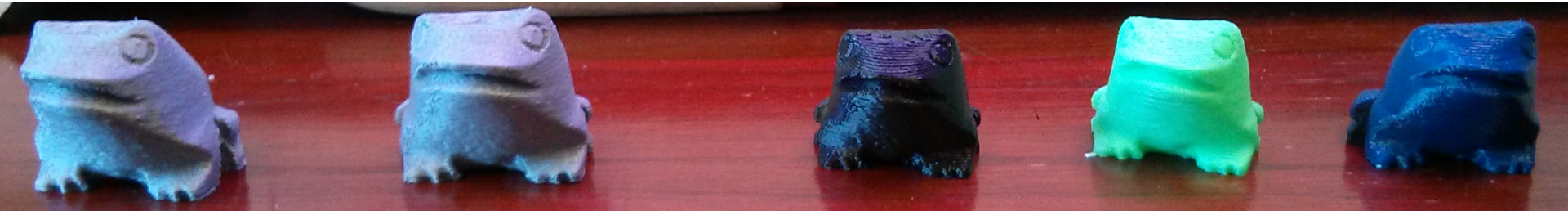
- Five 3D printers were tested
  - All 5 were the same popular commercial variety
  - All unenclosed designs

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

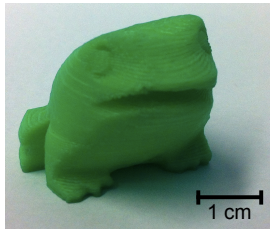
- Two types of filaments at different operational conditions
  - 2 PLA @ 200°C nozzle T and 18°C bed T
  - 3 ABS @ 220°C nozzle T and 118° bed T

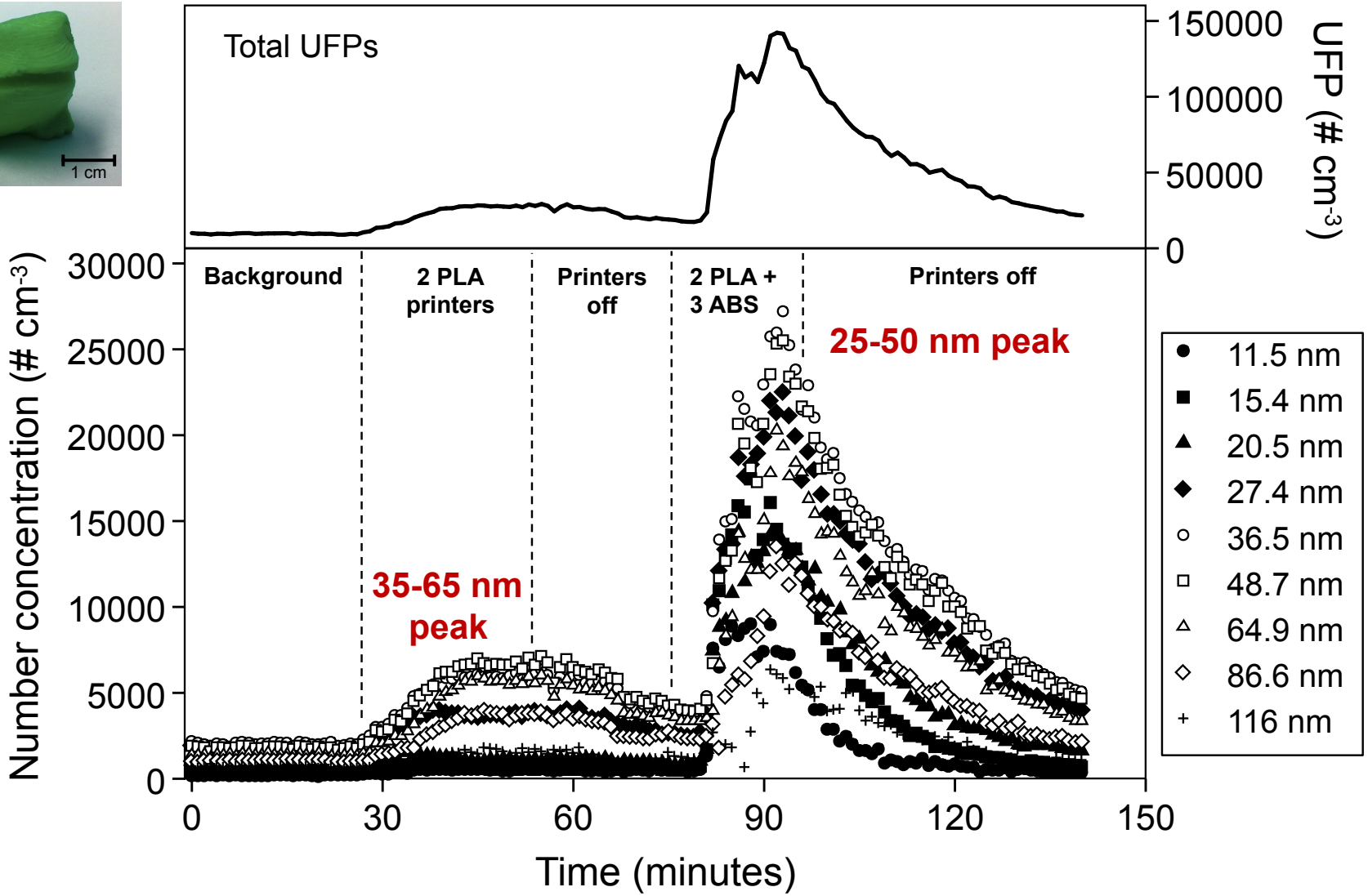
- Operating in a closed 45 m^3 office environment

- Ultrafine particle concentrations measured w/ TSI NanoScan SMPS Tritscher et al. **2013** *J Physics* 429



Measured ultrafine particle concentrations





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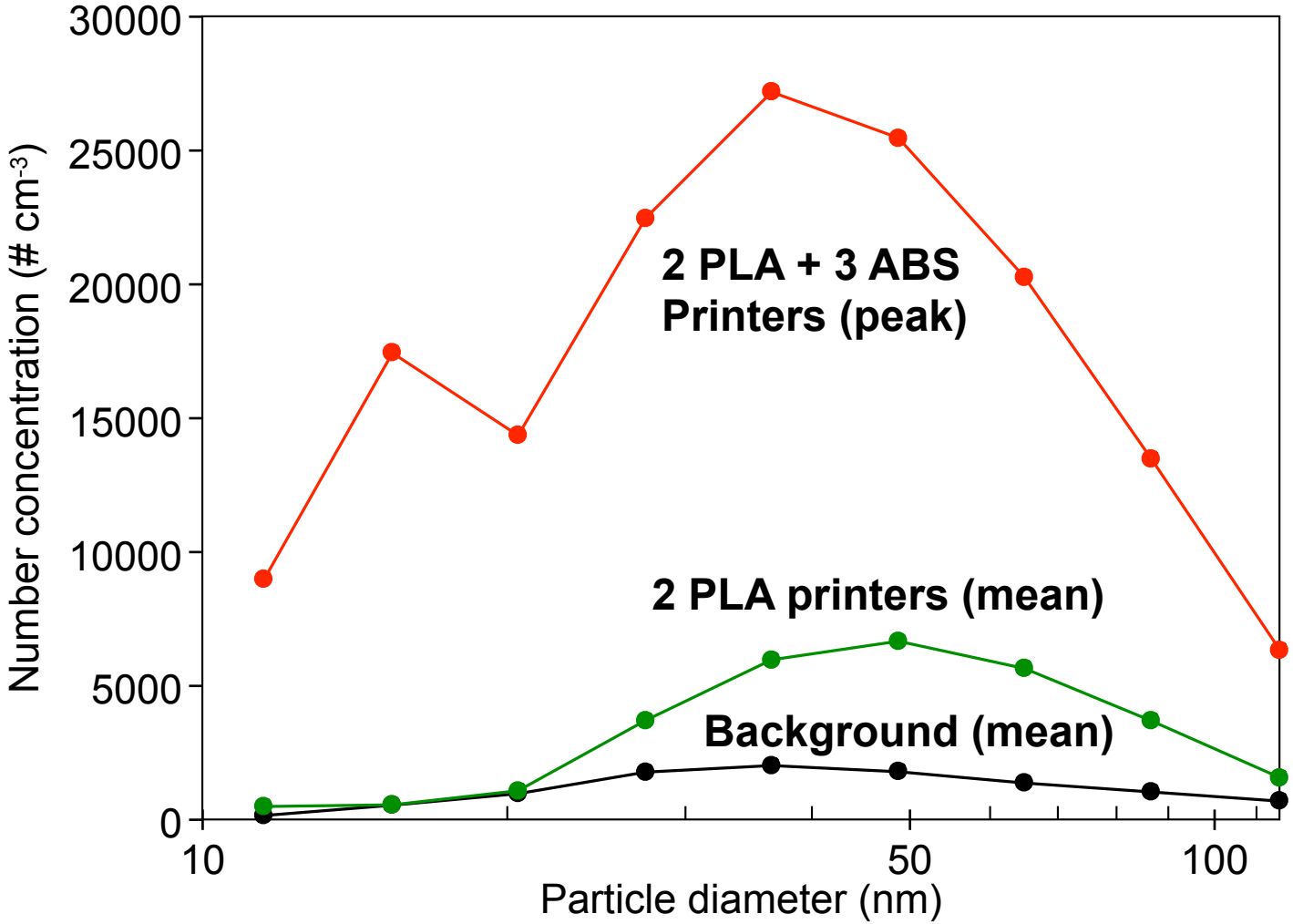
Mean and peak UFP size distributions



UFP summary
Background mean
~10,000 #/cm^3
2 PLA mean
~28,000 #/cm^3
2 PLA + 3 ABS peak
~142,000 #/cm^3

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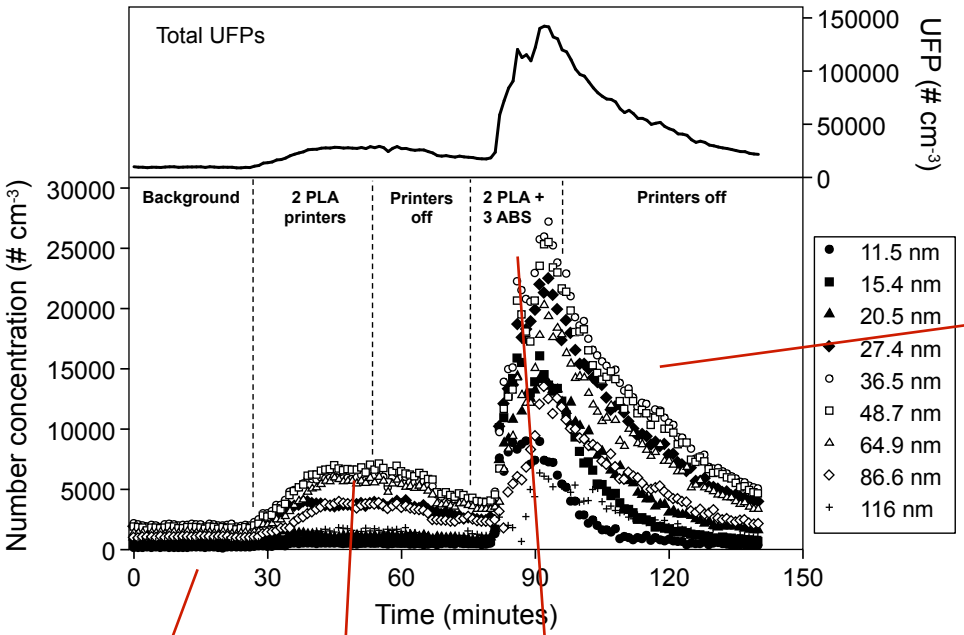
Estimating emission rates



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

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

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

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

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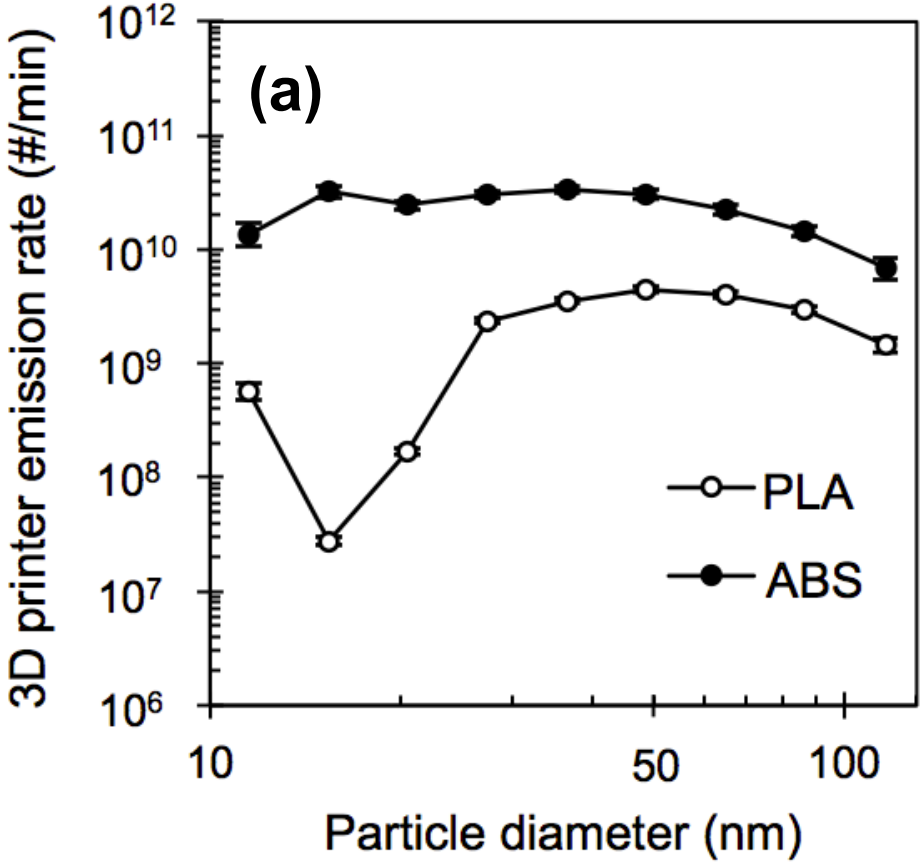
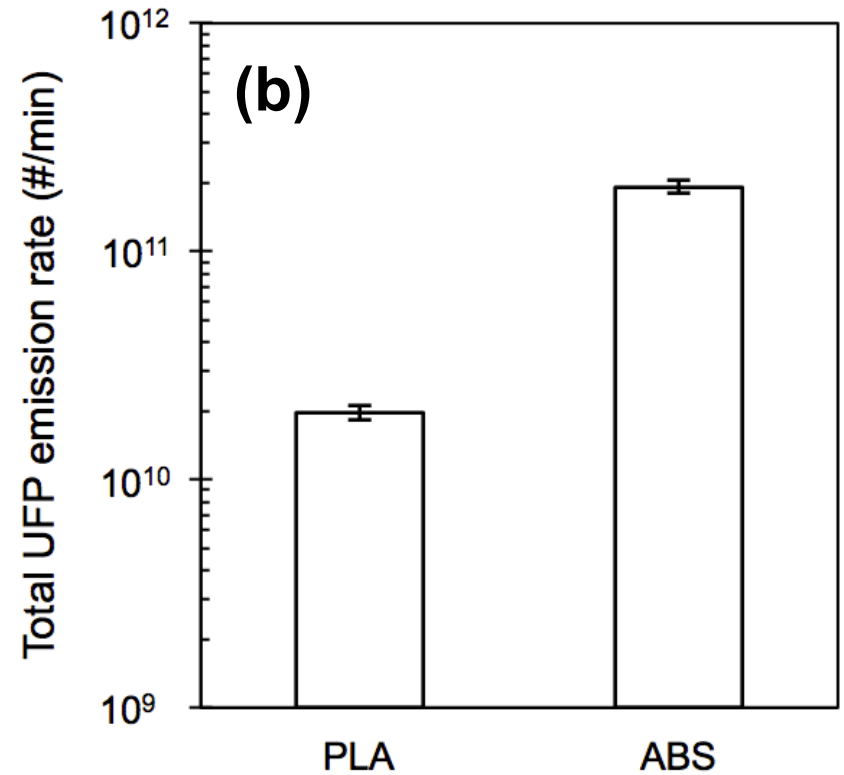
Size-resolved and total UFP emission rates





Total UFP emission rates:
~1.9×10^{11} #/min from ABS printer
~2.0×10^{10} #/min from PLA printer

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Comparison of emission rates to other indoor emitters

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)

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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'

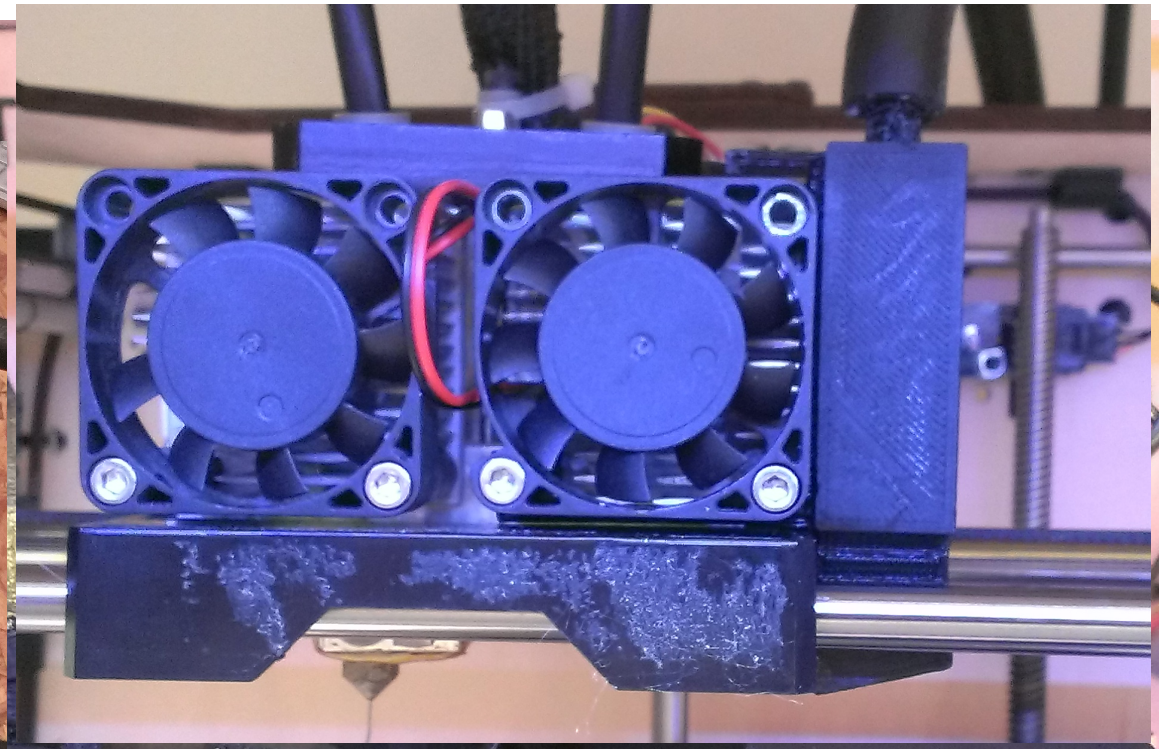
StreetInsider.com

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

Moving forward

- We could use more measurements
  - More printers
  - More filaments
  - Particles and gas-phase compounds
  - In realistic environments
- We could use inhalation toxicology studies
  - Cell lines, mouse models, human subjects
- Or we can jump directly to control strategies
  - Filtration, ventilation, enclosures

Potential for 3D printed 3D printer filtration systems



Photos courtesy Mike Moceri, The 3D Printer Experience

Acknowledgments

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- The 3D Printer Experience, Chicago, IL

Questions/Comments

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