Dynamics of Exhaled Respiratory Aerosols

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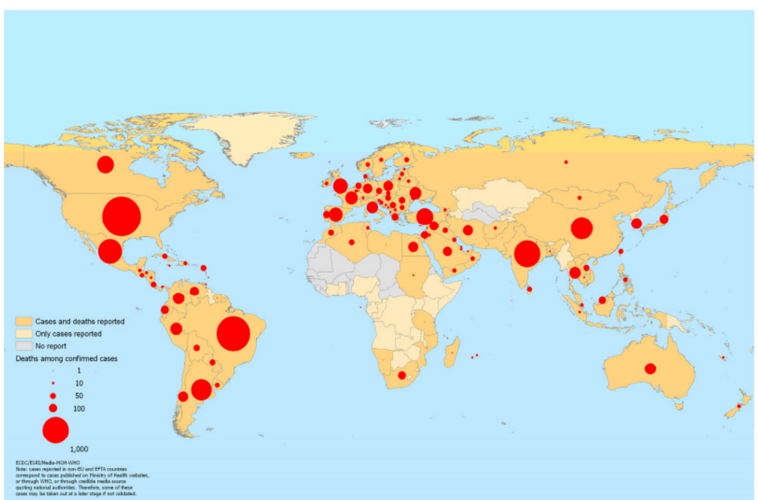
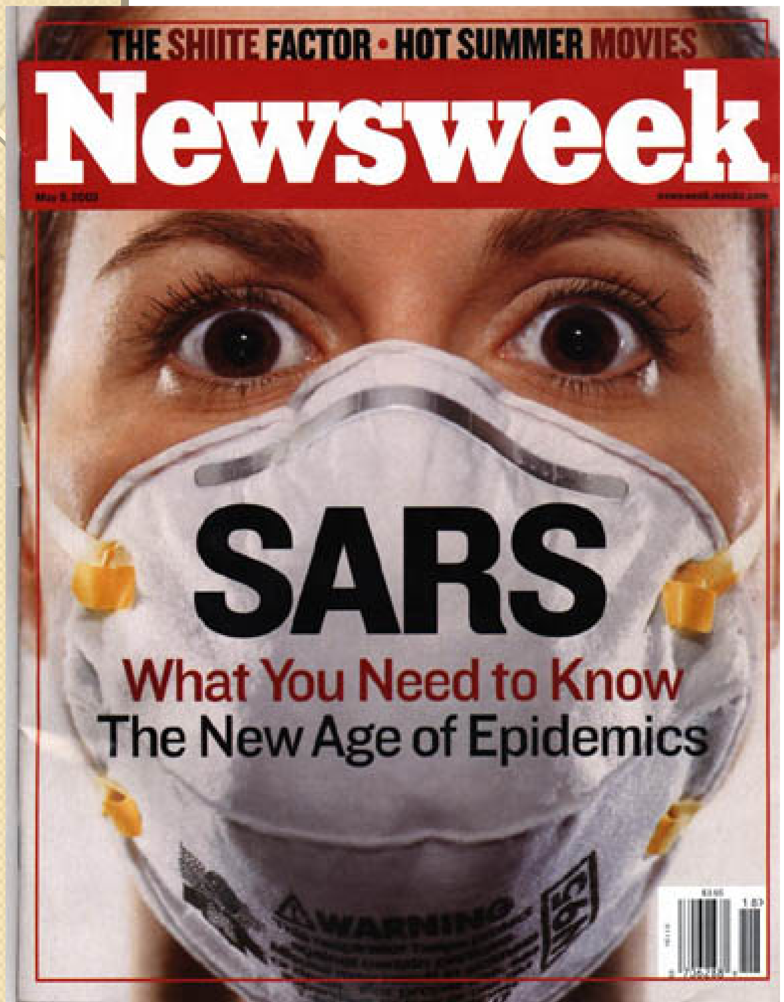
2009 H1N1 epidemic

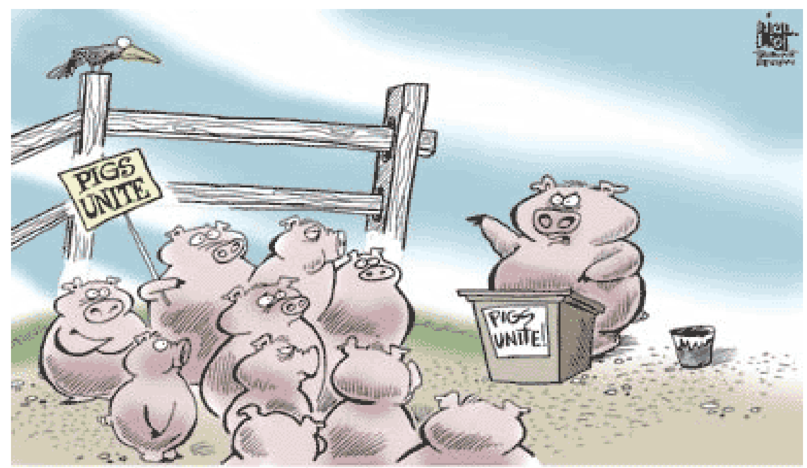
- First case appeared in Apr 09 in Veracruz, Mexico
- Cases reported in more than 206 countries



- Worldwide
  - Over 526060 verified cases
  - At least 12220 deaths
- (WHO, Dec 20th 2009)

- Israel
  - 10,267 verified cases
  - 90 deaths
- (Ministry of Health, Israel, Feb 2nd 2009)





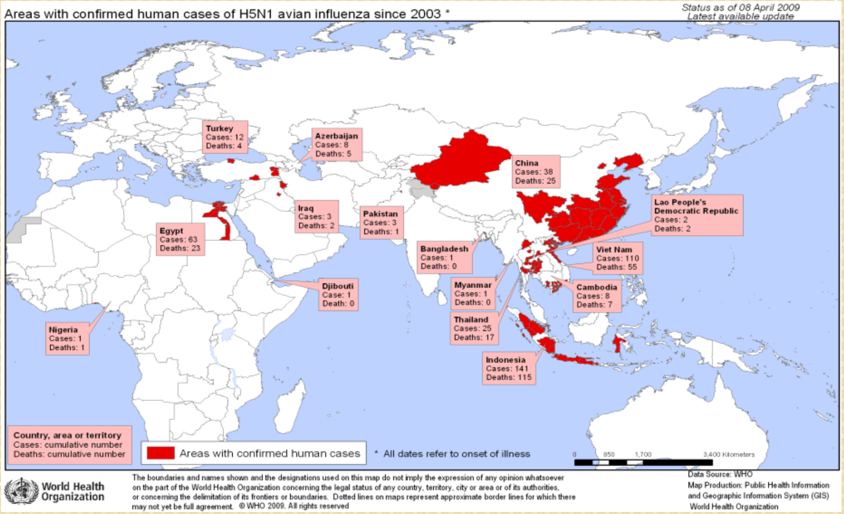
THE TURKEYS HAVE BIRD FLU. THE COWS HAVE MAD COW DISEASE. I'M TELLING YOU, BOYS... UNLESS WE WANT TO SEE MORE HAM SERVED ON THANKSGIVING, WE'RE GOING TO HAVE TO GET OUR OWN DISEASE!

SARS

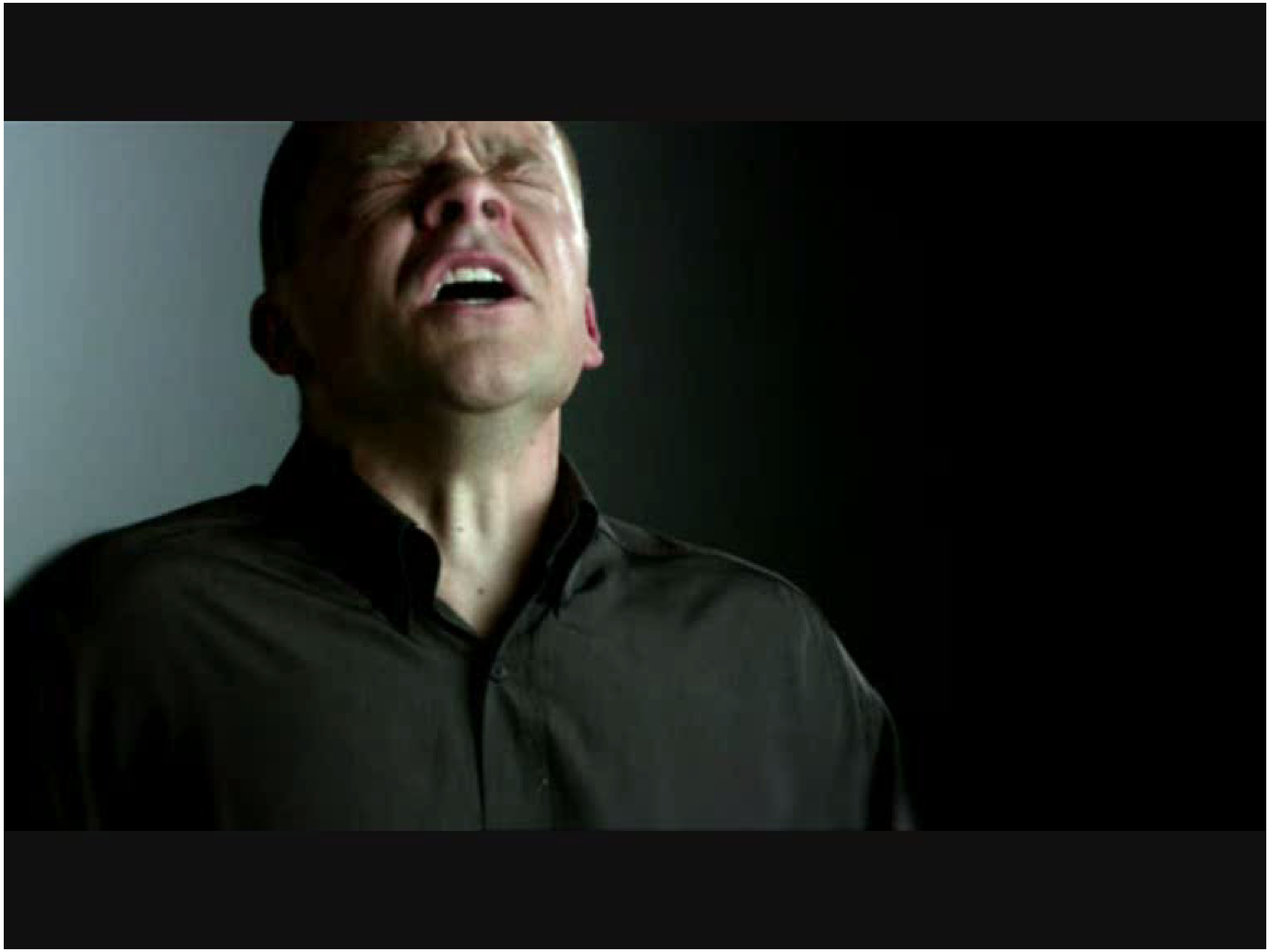
- Severe acute respiratory syndrome
- From Nov 02 to Jun 03
- Over 8000 cases
  - 774 reported deaths

Avian Flu (H5N1)

- First case Dec 03, Vietnam
- 420 verified cases worldwide
  - 257 deaths



Respiratory Diseases



Direct droplet contact

- Direct contact with large droplets
- Effective only in short distances

Airborne route

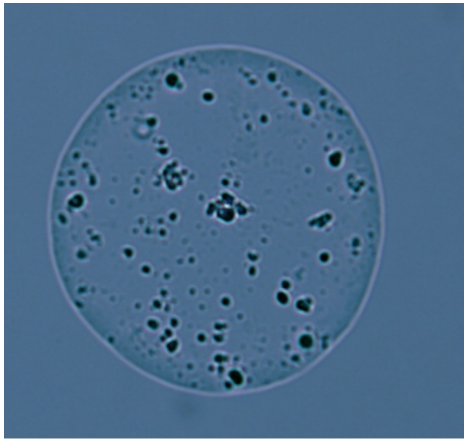
- Droplet nuclei suspended in air
- Droplets reach farther and remain longer

Routes of transmission

Expiratory Droplet Investigation System (EDIS)

Expiratory Droplets

- Droplets emitted from the respiratory tract during cough, speech, sneezing etc.
- Droplets originate from the mucus in the airways



- Initial Composition

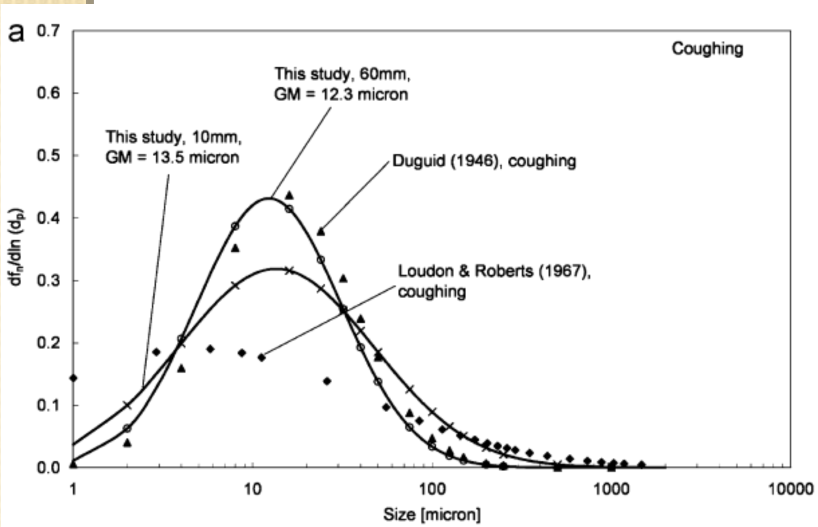
TABLE I. Major Components of Mucus

Species	Molecular Weight or Atomic Mass	Concentration
Na^+	23 g	91 ± 8 mM
K^+	39.1 g	60 ± 11 mM
Cl^-	35.5 g	102 ± 17 mM
Lactate	89 g	44 ± 17 mM
Glycoprotein	not given	76 ± 18 g/L

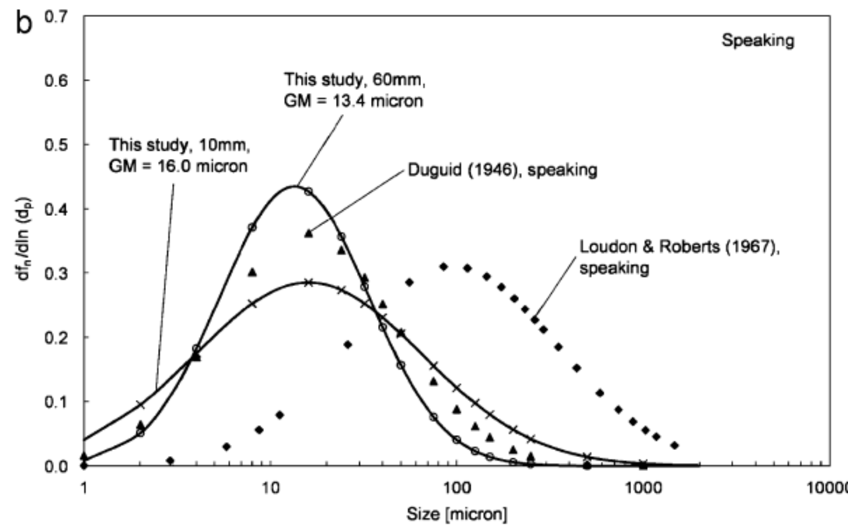
Source: Data from Effros et al., "Dilution of Respiratory Solutes in Exhaled Condensates." *American Journal of Respiratory and Critical Care Medicine* 165:663–669 (2002).

Size Distribution

Coughing



Speaking



Range: 2-1000 μm
80% under 30 μm

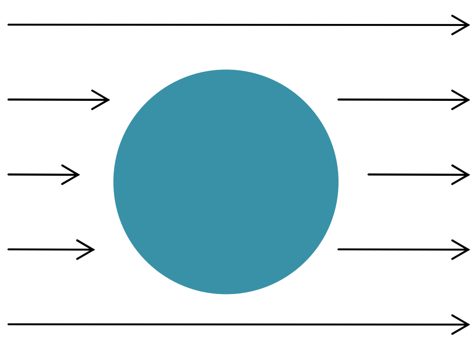
Area = Number of Particles

Chao et al. Aerosol Science 40 (2009) 122-133

THE MODEL

Two Phase Flow

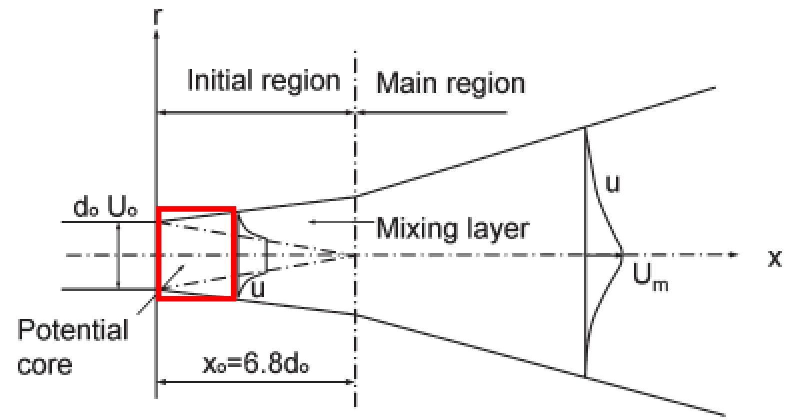
- Discrete Phase
  - Hygroscopic Droplets
  - Emitted during cough, speech, sneezing etc.
  - Body temperature



- Continuous Phase
  - Air exhaled form the respiratory tract
  - High content of water vapor
  - Body temperature
  - Velocity ranges from 3.9m/s (speech) to 11.7m/s (cough)

Turbulent Round Jet

- Distribution of exhaled air's velocity, temperature and humidity



- Axisymmetric jet
- Exits at an angle θ above the horizon

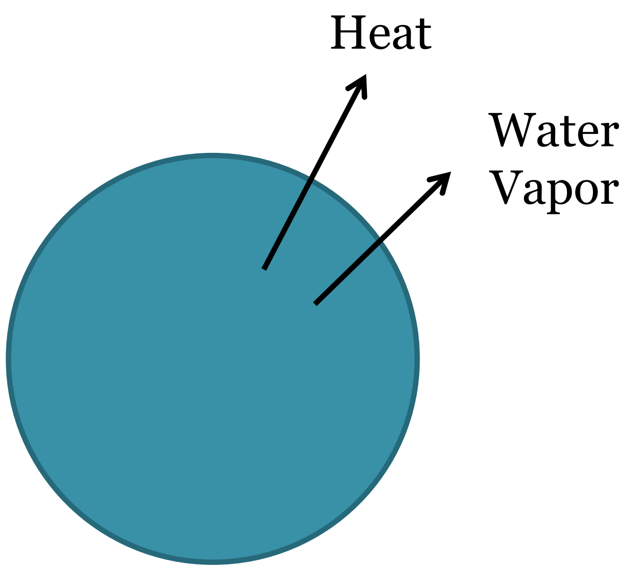
$$Re \approx 10^4$$

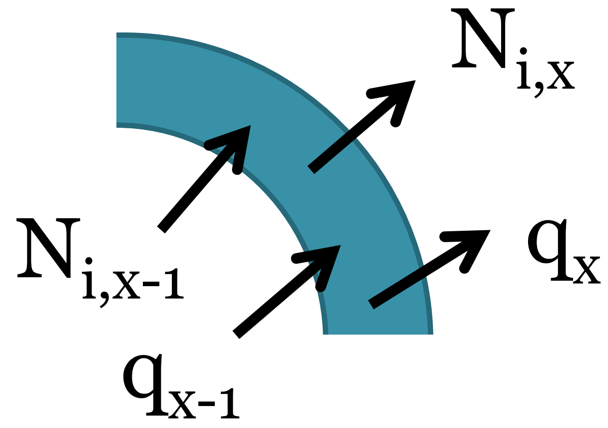
- Composed of
  - Potential core (or ZFE)
  - Main region (or ZEF)

- Thermal diffusivity
  $\alpha = \kappa / \rho c_p = 0.24\ cm/s^2$
- Kinematic viscosity
  $\nu = \mu / \rho = 0.16\ cm/s^2$

Droplet Evaporation Models

- Uniform Droplet
- Multi-Shells Droplet



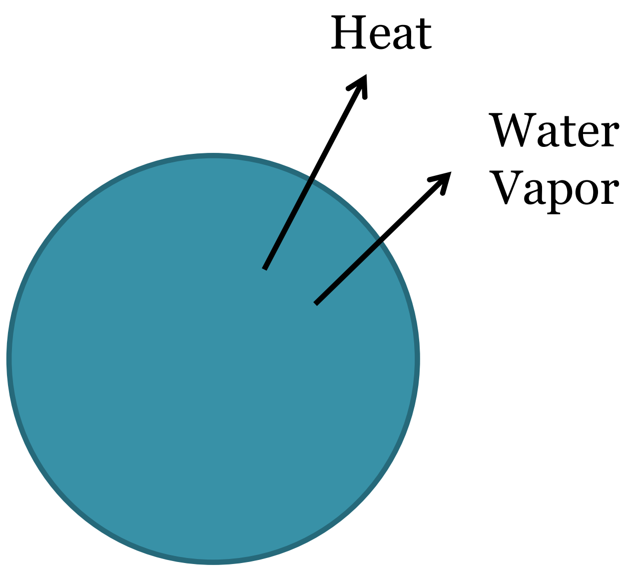


Droplet Evaporation

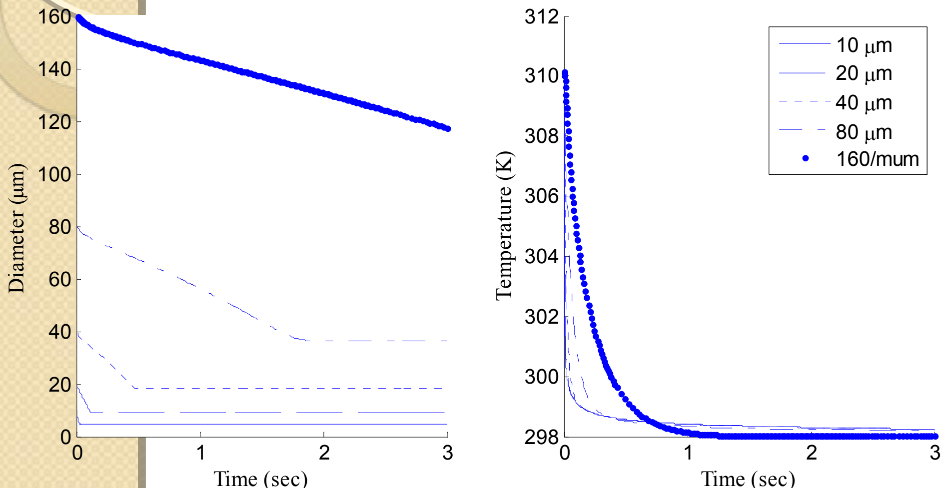
- Only water evaporates
- Induced by forced convection

$$\frac{dm_p}{dt} = 4\pi R_d^{\,2} Kd(\rho_{ws} - \rho_{w\infty})$$

$$\frac{dT_s}{dt} = 4\pi R_d^{\,2} h(T_s - T_\infty)$$

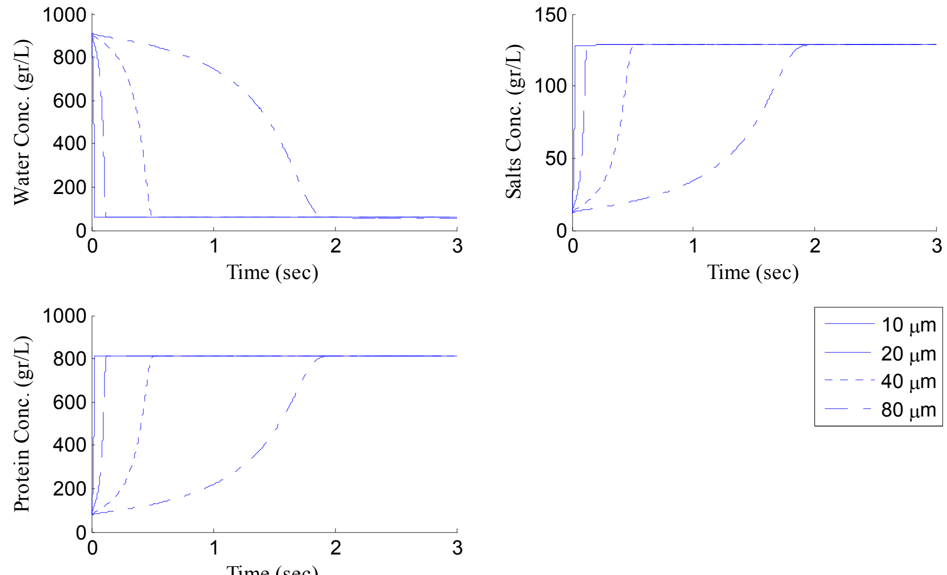


Effect of droplet size



Change in droplet diameter and temperature

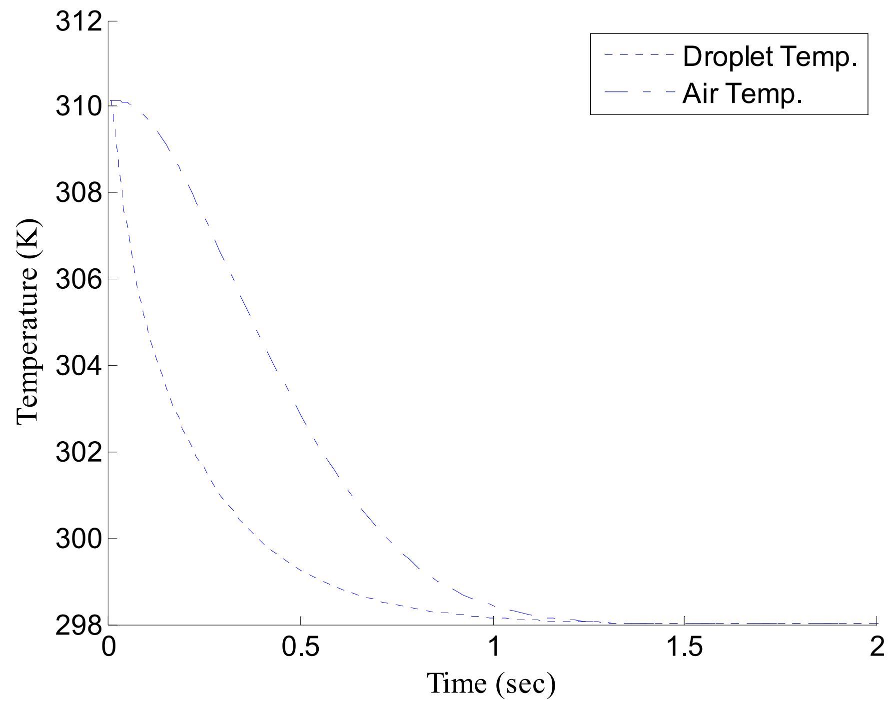
The change in concentration of different species at the surface



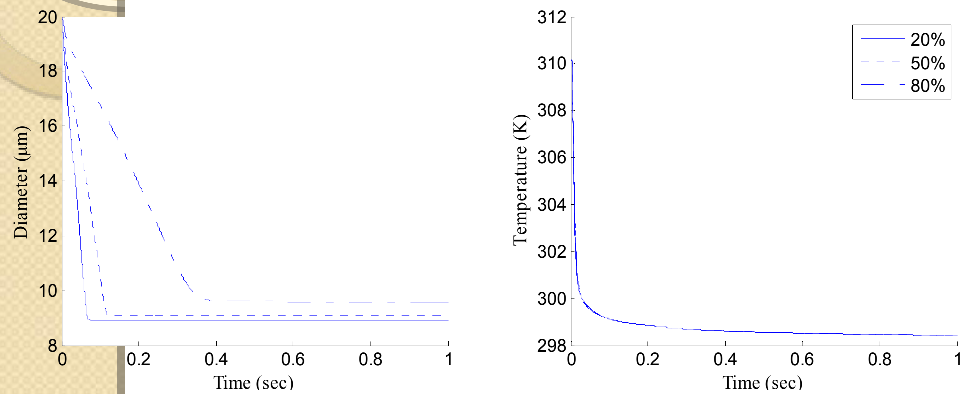
Droplet Temperature

- Temperature of the travelling droplet and the surrounding air parcel

- Droplet temperature is lower than surrounding air due to evaporation



Effect of relative humidity



Change in droplet diameter and temperature

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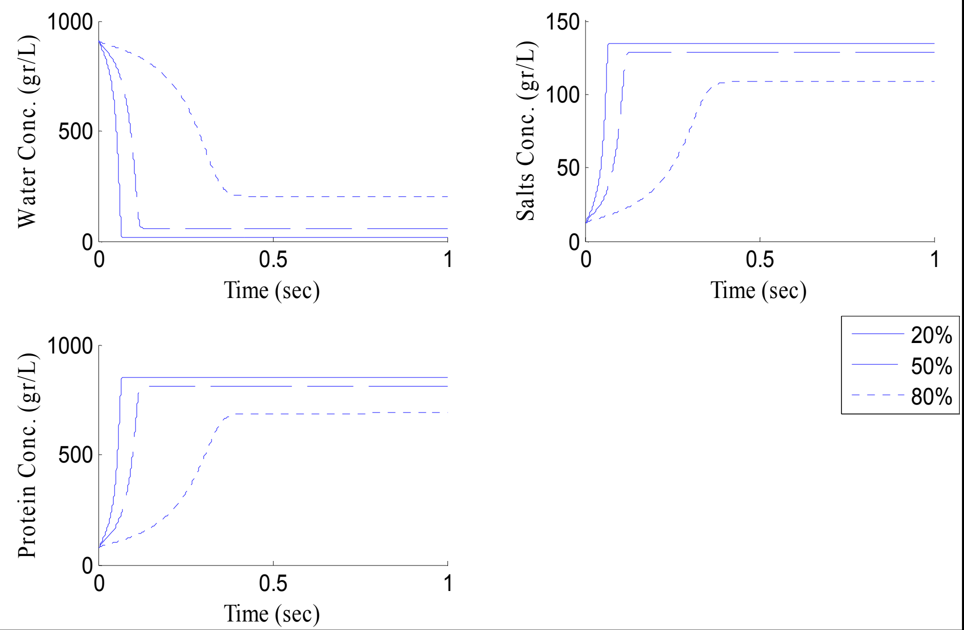
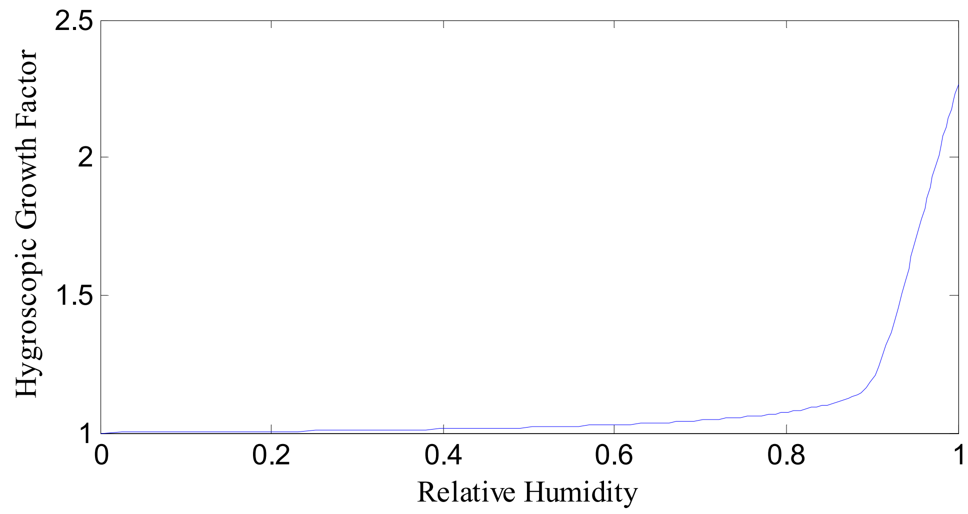


Hygroscopic growth factor

- HGF is the ratio of equilibrium diameter to dry droplet diameter



- For comparison the ratio of the initial diameter to dry droplet diameter is 2.25

Convective Transport

- Convective mass transfer

$$\frac{dm_p}{dt} = 4\pi R_d^{\;2} Kd(\rho_{ws} - \rho_{w\infty})$$

- Convective heat transfer

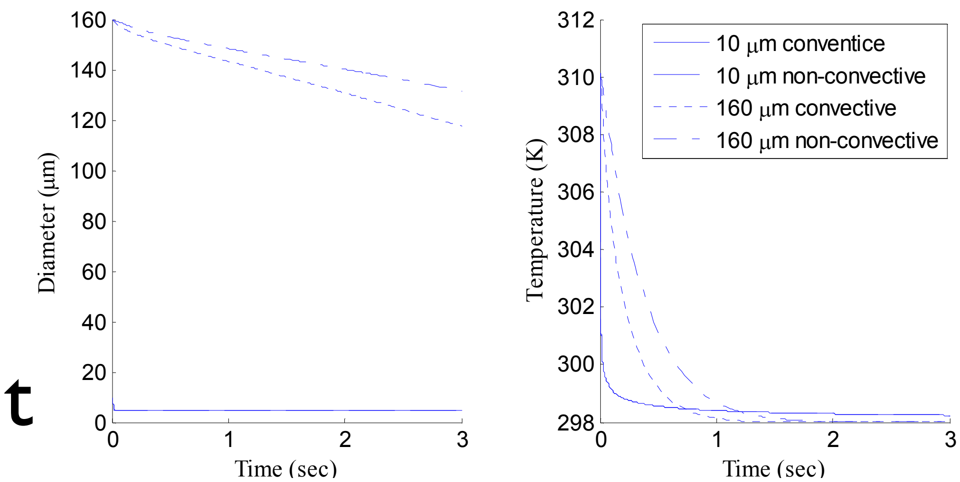
$$\frac{dT_s}{dt} = 4\pi R_d^{\;2} h(T_s - T_\infty)$$

- Ranz-Marshall correlations

$$Sh = \frac{K_d D}{D_g} = 2 + 0.6\,\mathrm{Re}_p^{\;1/2}\, Sc^{1/3} \qquad Nu = \frac{hD}{k_g} = 2 + 0.6\,\mathrm{Re}_d^{\;1/2}\, \mathrm{Pr}^{1/3}$$

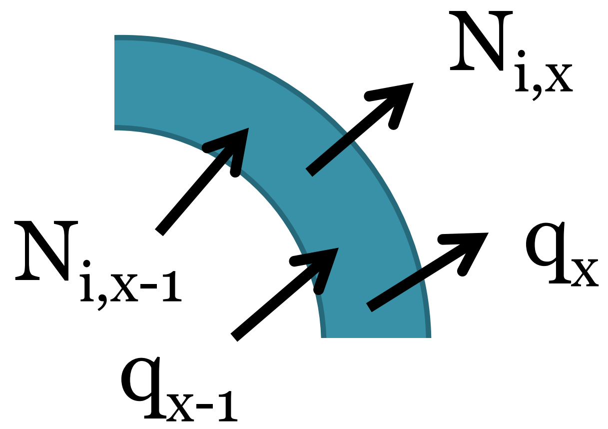
Convective vs. non-convective transport

- Convective transport affects mainly large droplets.
- Small droplets don't generate high velocity differences



Multi-shells model

- Gradients and Fluxes within the droplet
- Shells with unique characteristics and identical thickness



Mass Flux:

$$N_{i,x} = J_{i,x} + \rho_{i,x} \frac{x}{S_n} \frac{dR_d}{dt}$$

$$J_{i,x} = -\frac{D_i}{R_d / S_n} \left(\rho_{i,x+1} - \rho_{i,x} \right)$$

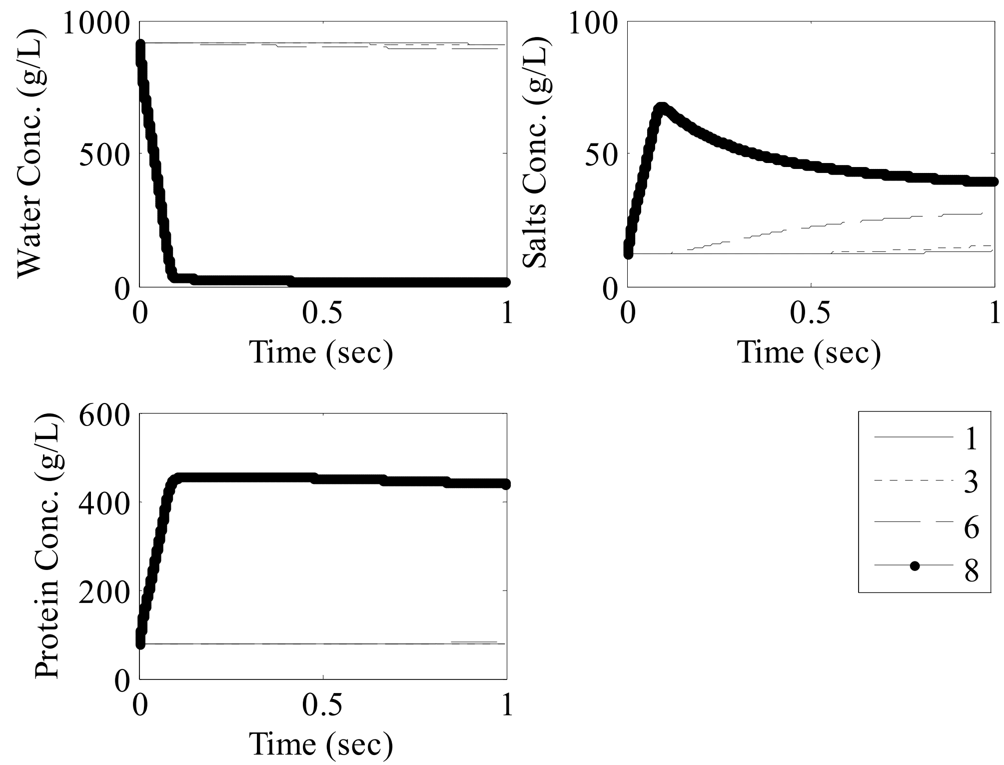
Heat Flux:

$$q_x = -\frac{k_w}{R_d / S_n} \left(T_{x+1} - T_x \right)$$

Diffusion coefficient determined by Stokes-Einstein correlation

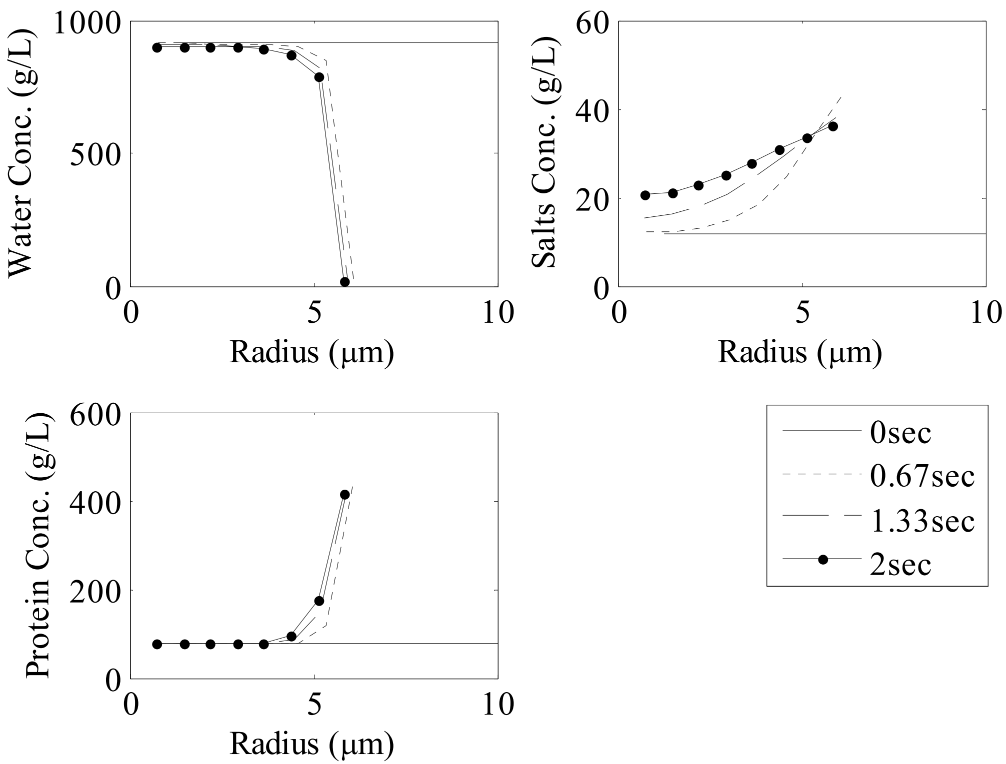
Inner composition of droplets

- Change in Concentration at different shells
- Behavior dictated by evaporation and diffusion



Inner composition of droplets

- Concentration profile at several times during the evaporation

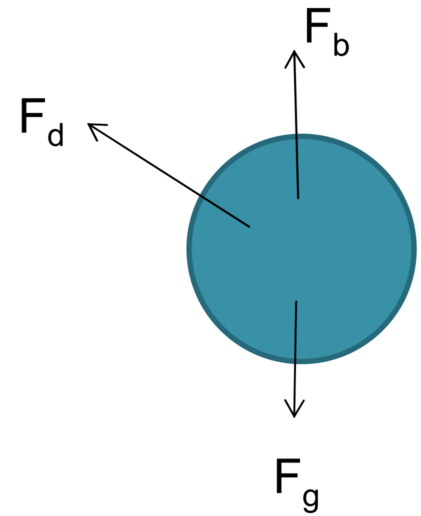


Droplet motion

- 3 major forces
  - Gravity $F_g = m_d g$
  - Buoyancy $F_b = \rho_a V g$
  - Drag $F_d = 3\pi\mu D_p (u - v)$

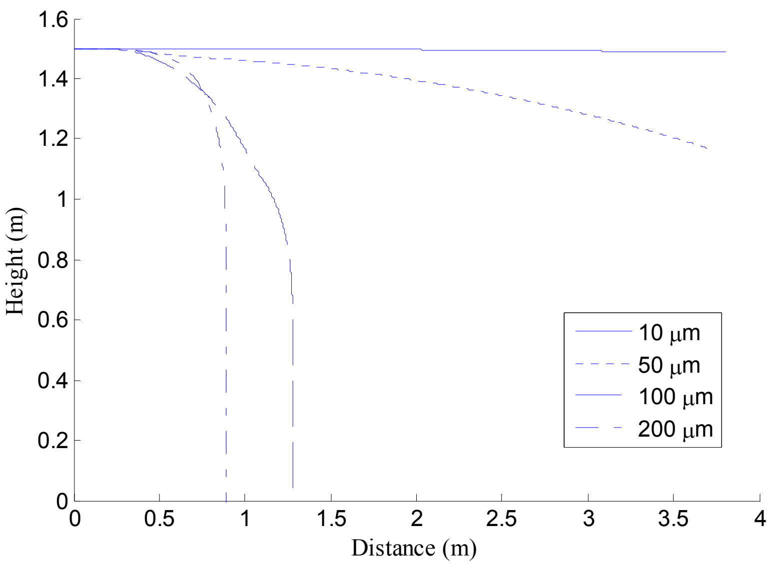
$$F_d = \frac{1}{2}\rho_a |u - v|(u - v) C_d A_s \quad \mathrm{Re}_p > 1$$

$$\sum F = \frac{d}{dt}(m_p v)$$

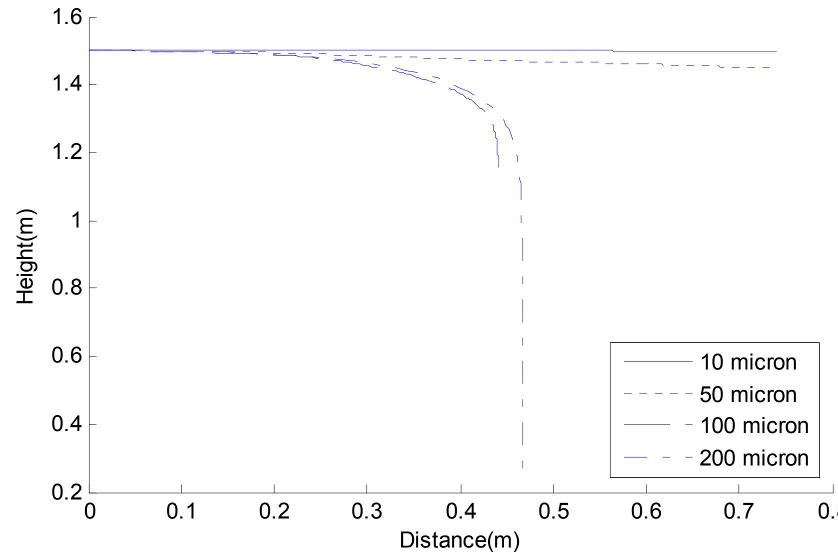


Droplet Trajectories

- Trajectories for droplets of various sizes during coughing or speaking



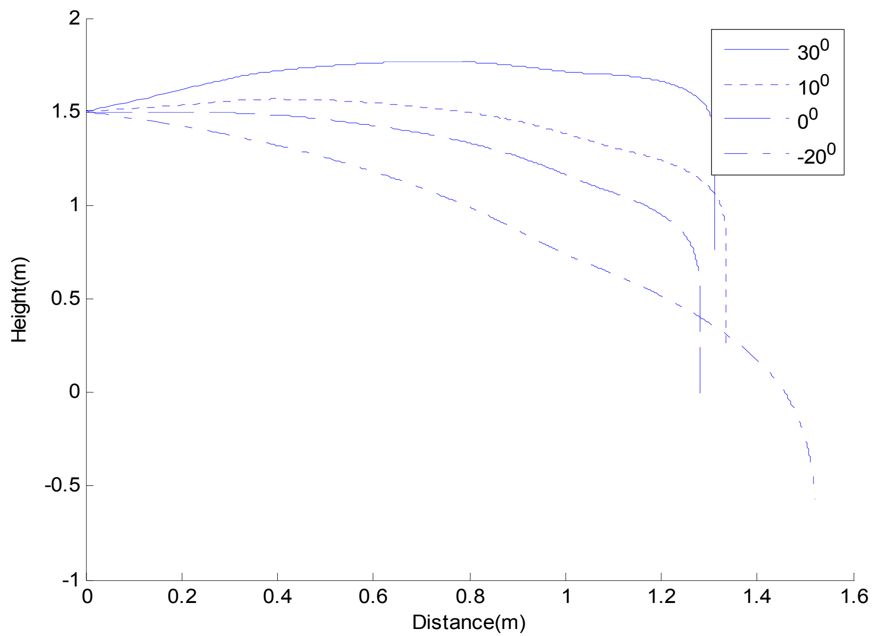
Cough (11.7m/sec)



Speech (3.9 m/sec)

Droplet Trajectories

- Both the jet and the droplet exit at an angle θ above the horizon
- Droplets exiting at a negative angle remain longer in the jet's area of influence



Conclusion

- The model can be used to predict evaporation and motion of exhaled droplets
- The model helps quantify the effects of various elements on droplet dynamics
- Results support the distinction between droplet contact and airborne transmission
- Droplet evaporation is characterized by two distinct stages

References

- Chao C.Y.H et al., "Characterization of expiration air jets and droplet size distributions immediately at the mouth opening", Aerosol Science 40 (2009) 122--133
- Morawska L. et al., "Size distribution and sites of origin of droplets expelled from the human respiratory tract during expiratory activities", Aerosol Science 40 (2009) 256--269
- Parienta D. et al., "Dynamics of exhaled respiratory droplets", Aerosol Science, to be submitted

Thanks

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Questions?