Glass Processing Lectures at Lehigh University –
Lecture 06: Fusion Forming

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Lectures available at:
www.lehigh.edu/imi

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We hope you have or leave with

1. A base understanding of Volume-temperature curves and glass behavior
   – Transition temperature
   – Thermal expansion
   – Stress/Strain

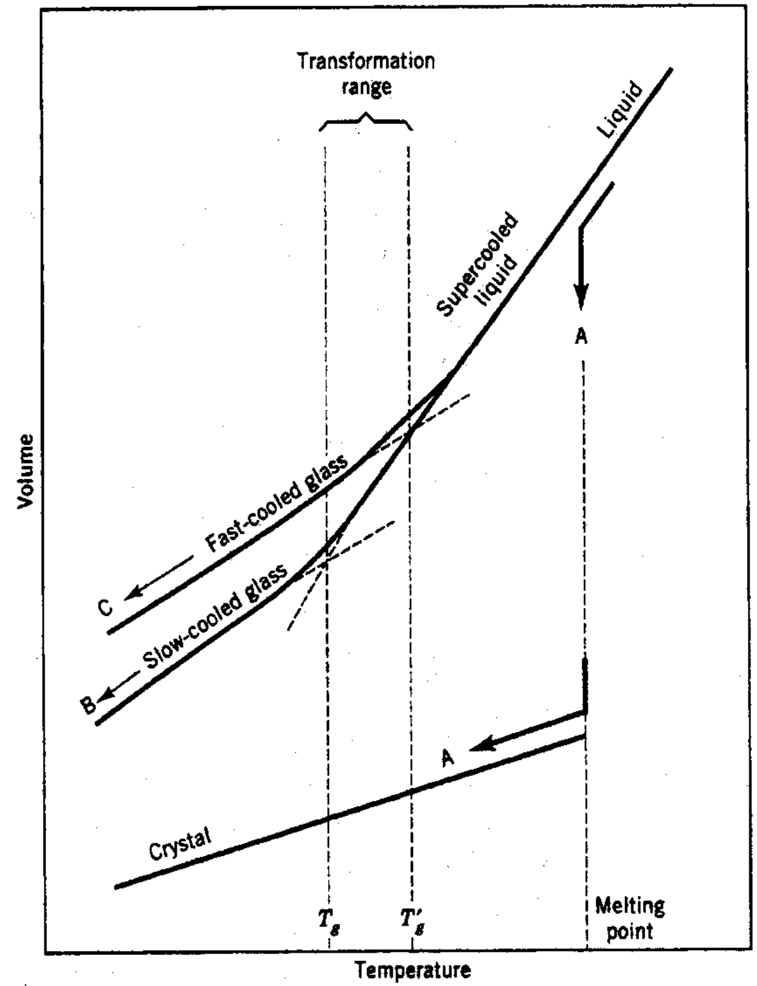
2. Awareness of viscous, visco-elastic and elastic regimes

My intent

- To introduce and provide a technical insight into process development principles
- To NOT bore you with math, but to “tickle the ivories” and provoke thought/interest in glass processing.
- To generate dialogue – hopefully continues beyond today
  - So,   please ask questions

First thought exercise – Two glasses cooled at different rates

1. What do we expect to see on the faster cooled glass on the chart?
   - Densification?
   - Fictive temperature?



First thought exercise – Two glasses cooled at different rates

1. What do we expect to see on the faster cooled glass on the chart?
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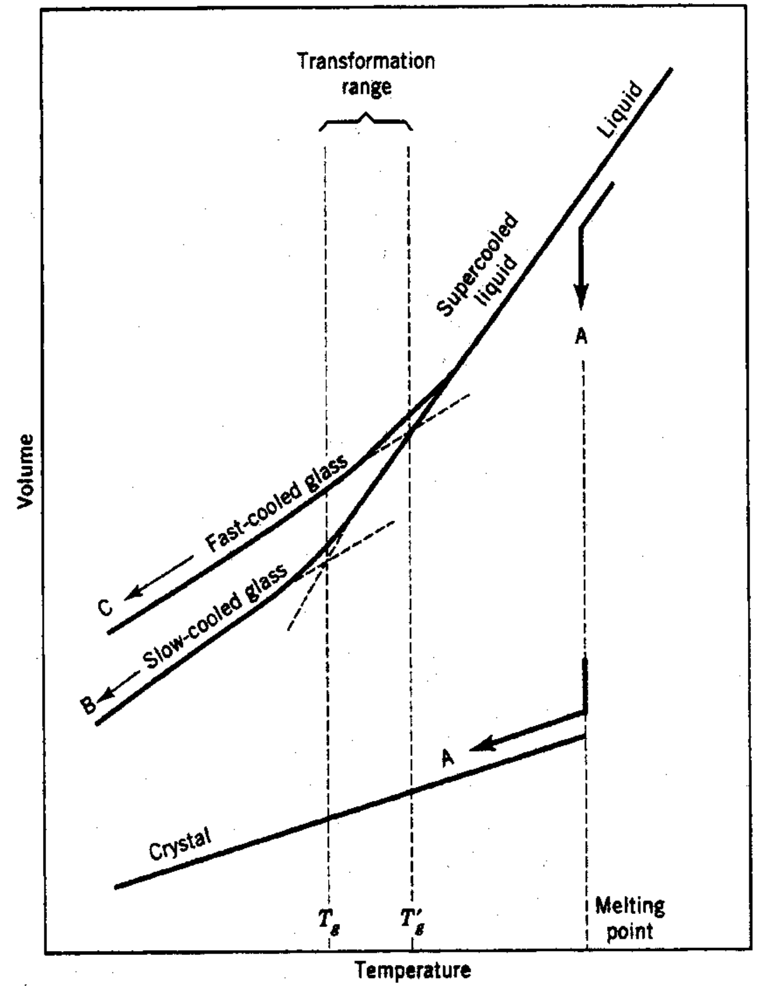
   - Fictive temperature?

2. Fictive temperature impacts
   1. Density
   2. Refractive index
   3. CTE
   4. viscosity

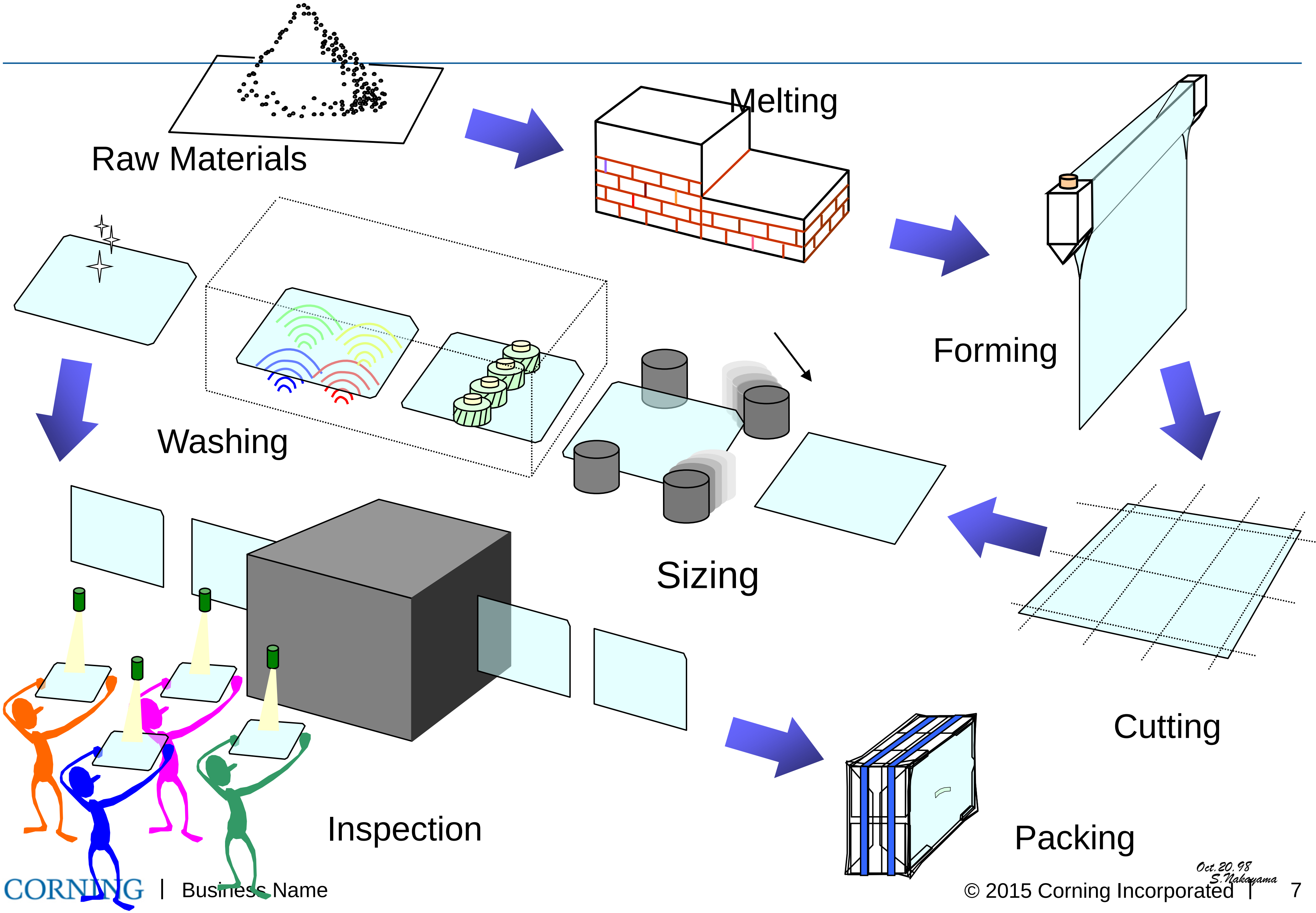
John Mauro's J Am Ceram Soc – 2009 article is a wonderful representation



Forming

- History of fusion forming development
- Key fundamentals

Schematic of a sheet manufacturing process



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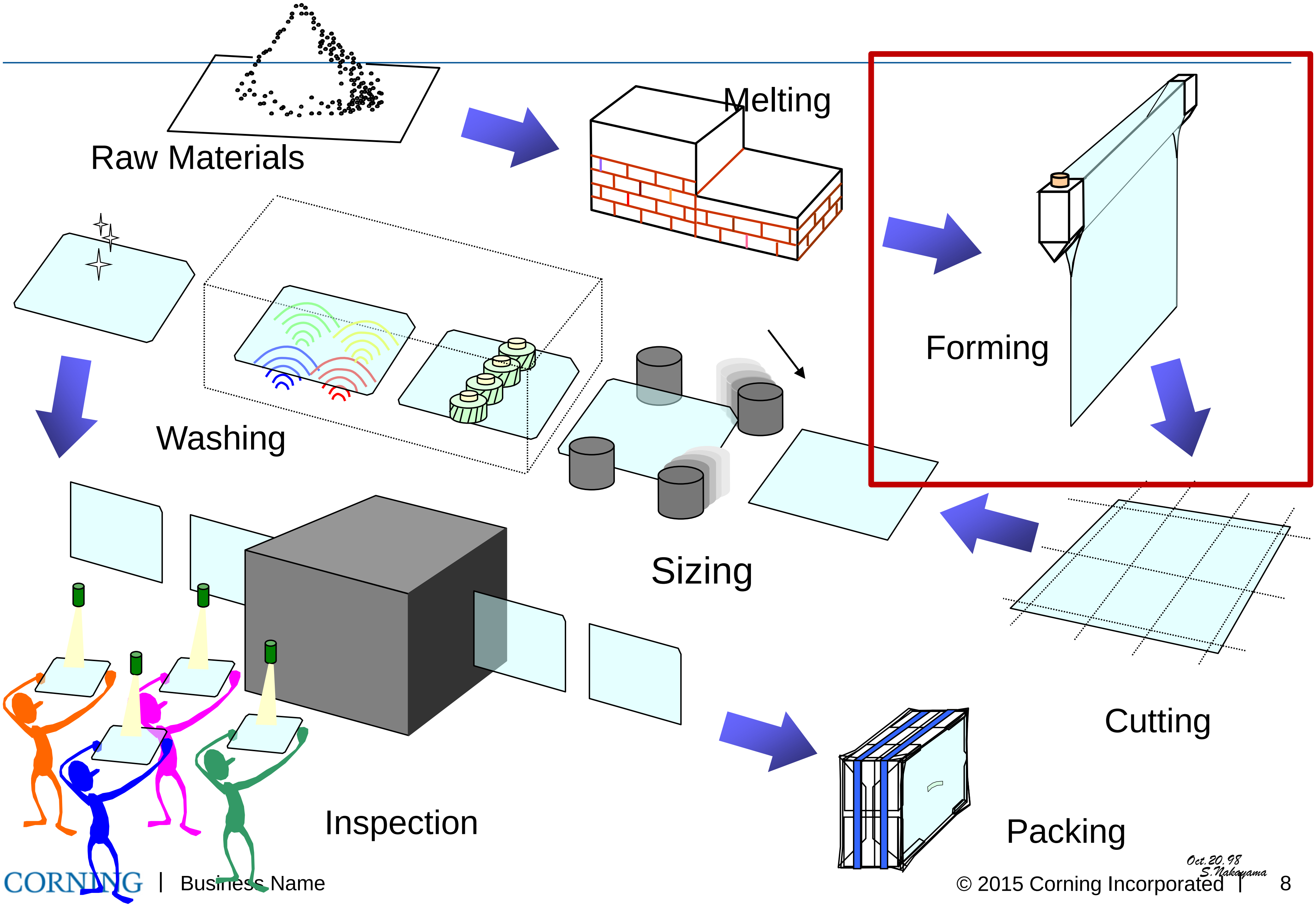
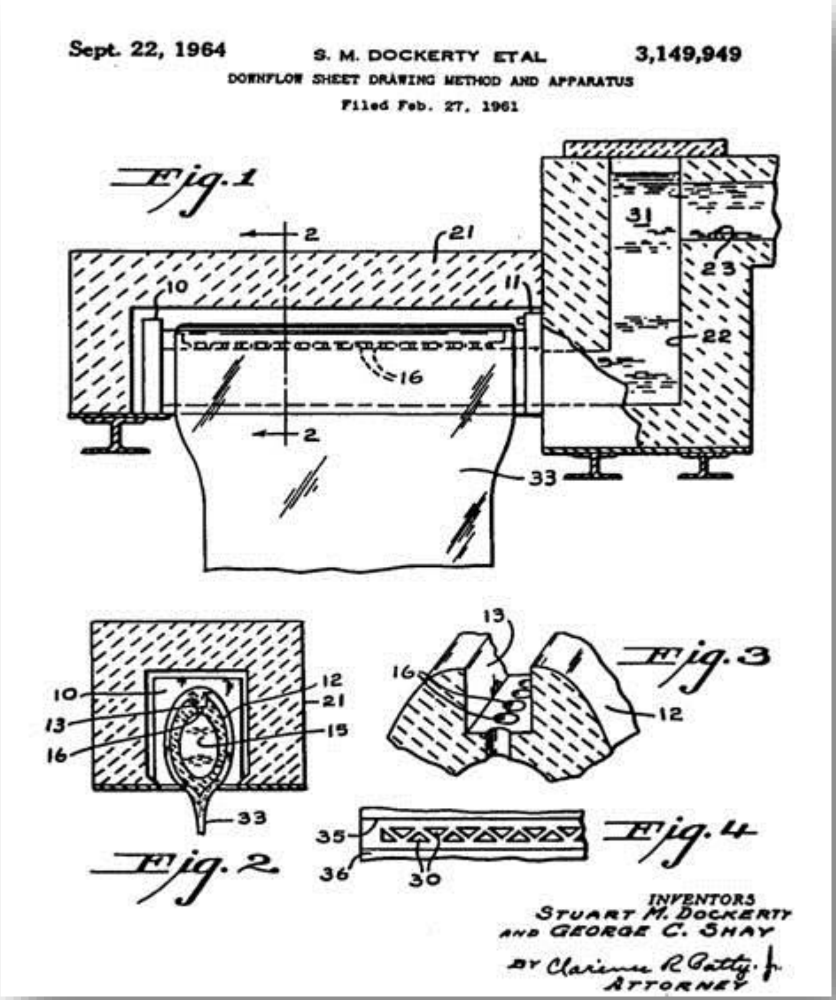
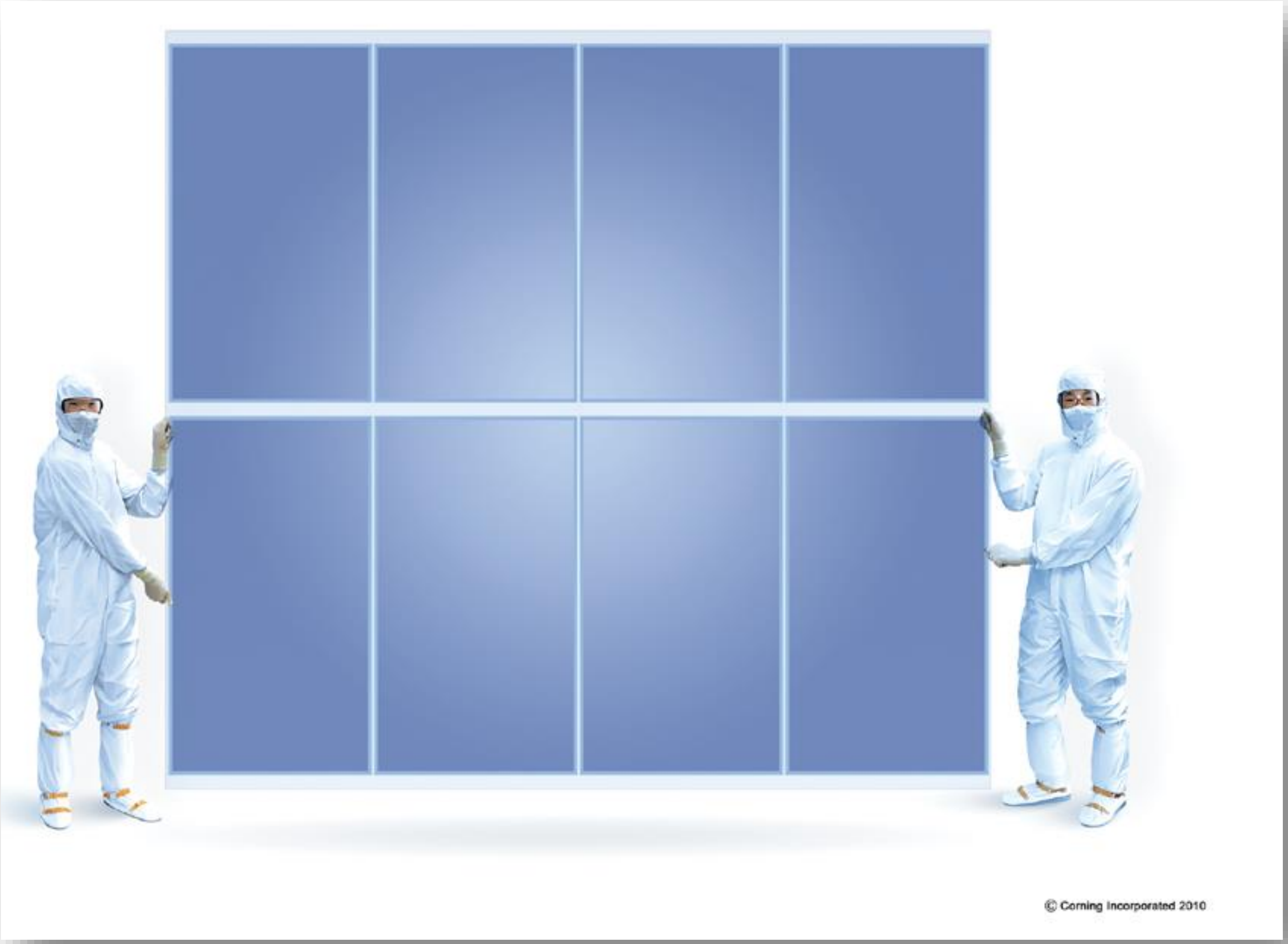


Corning developed the fusion overflow process more than 50 years ago



Glass making has evolved rapidly and now stretches to more than 3 meters wide



Glass forming covers a large range of viscosity

- In glass forming, viscosity ranges from ~10,000 Poise to Billions of Poise
  - Changes by 10+ orders of magnitude from melt through form!
  - Some critical figures of merit in forming
    - Softening ~$10^{7.6}$ Poise
    - Glass transition ~$10^{12} – 10^{16}$ Poise

- Some references
  - Water - 1/100 Poise
  - Olive oils ~1 Poise
  - Fluff ~100K Poise

Fusion glass feeds a number of applications in a variety of sizes – all with unique characteristics

- Larger display devices like TVs, monitors
- Smaller devices like tablets, phones
- Cover glasses to protect your various display devices
- Other applications …

The electronics landscape innovates quickly and requires changes in the entire ecosystem

Applications:	Smart Phone	Tablet	UHDTV
			

Display Types:	OLED	LCD
Backplane Technologies:	Oxide TFT	LTPS
Some Glasses:	EAGLE XG®	Lotus XT

Could you describe some unique characteristics for each application?

- Target applications
- Large displays
- Small displays
- Cover glass

- Product characteristics
  - ?
  - ?
  - ?

Market trends directly impact glass requirements Requirements

Display Trends	Panel Maker Trends	Glass Substrate Requirements
High Resolution	OLED Display	Dimensionally Stable
Fast Response Time	OxTFT Backplane	Flatness
Low Cost	LTPS Backplane	Low Particles
Low Power Consumption	Small Device on Large Gen Size	Thermally stable (sag, creep, stress relax.)
Thin and lightweight	Thin and lightweight	Thin

To succeed in delivering value to the customer, we must

- Have a comprehensive understanding of the entire value chain
  - Customer requirements and trends impact glass substrate design
  - Substrate drives sub-process technologies
  - Each process technology impacts the other
  - Each step requires significant time and money
  - Recognize market continues to innovate faster

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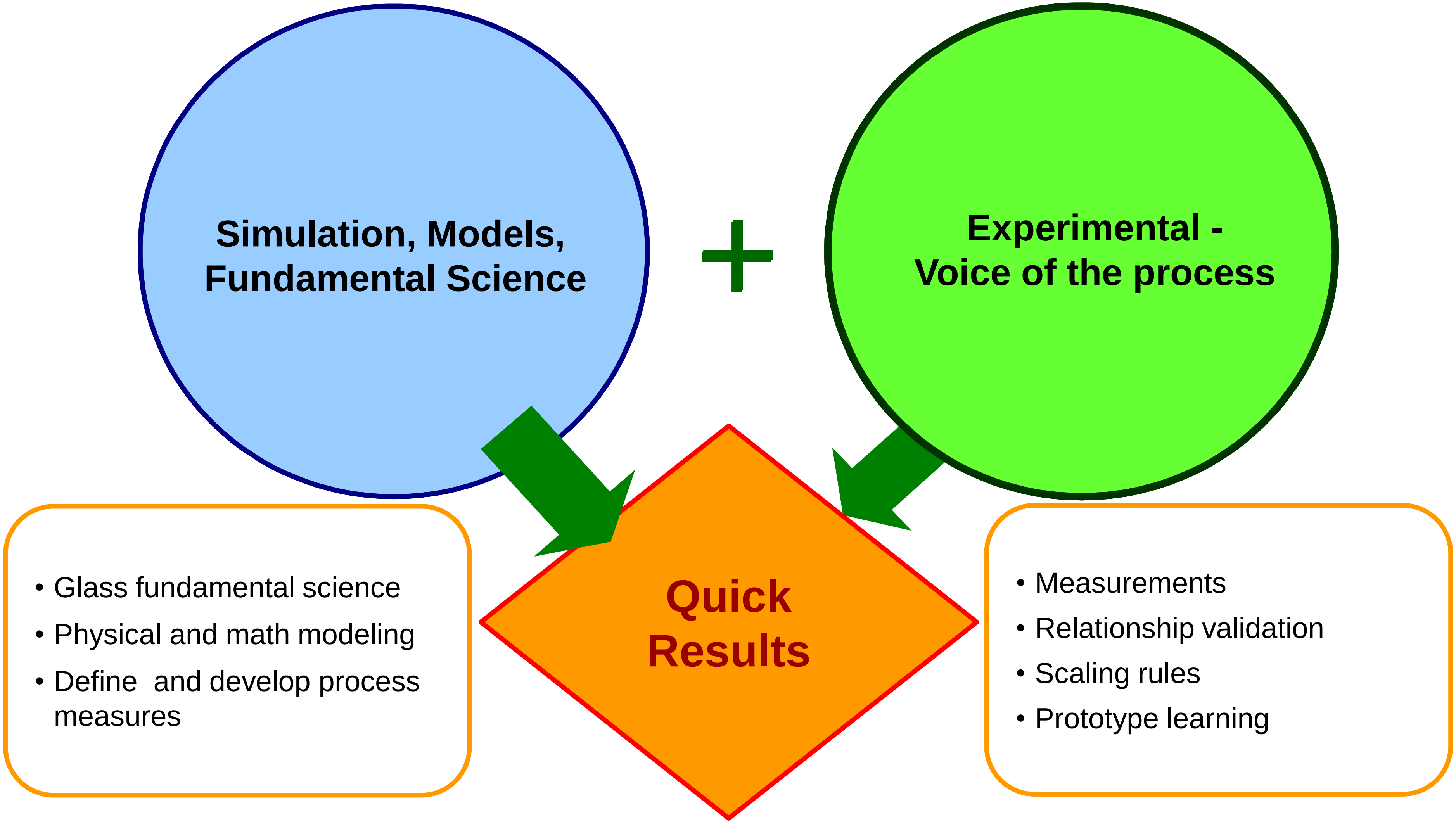
- Deliver differentiated solutions and customer value on a rapid timeline

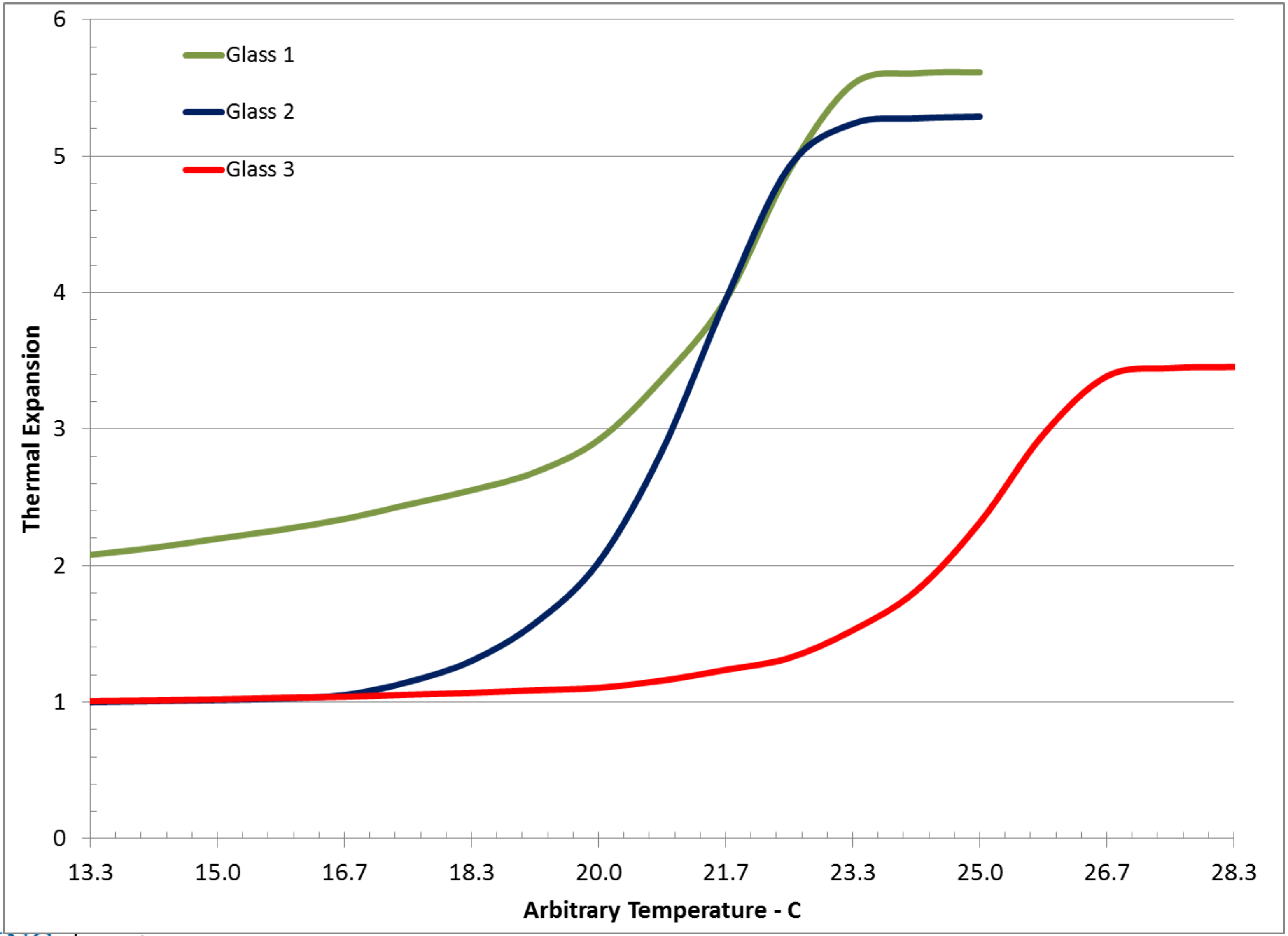
Glass substrate changes have a large process innovation impact

- New Melt technologies
- New Forming technologies
- New cutting and packaging technologies
- Some additives in glass help cutting, but hurt melting and forming
  - How do we optimize efficiently?
  - A target rich environment for technical innovation. ☺

Rapid Innovation requires a combination of fundamental science and experiments

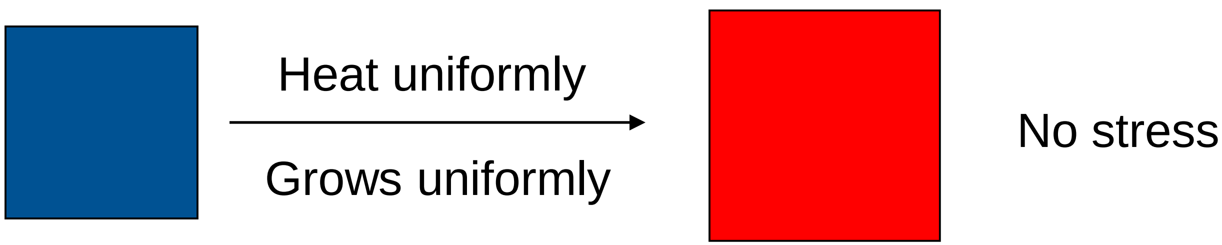


Since glass thermal expansion changes with temperature, each application may require unique solutions

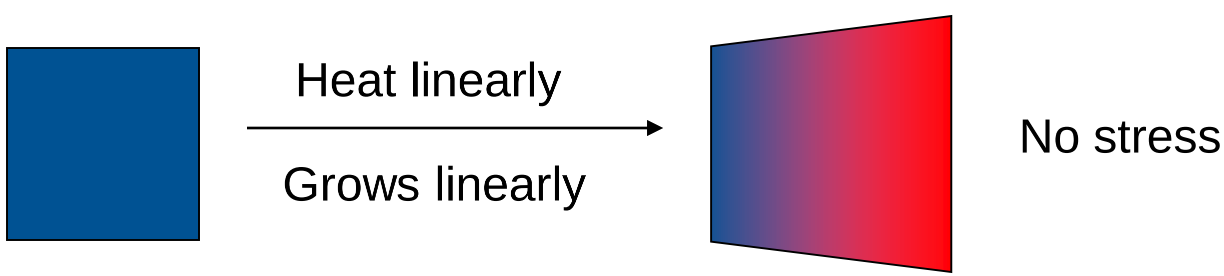


Fundamentals - Thermal strain and stress

- There are temperature fields that add no stress to a glass sheet.
  - Increasing glass temperature uniformly does not change stress.

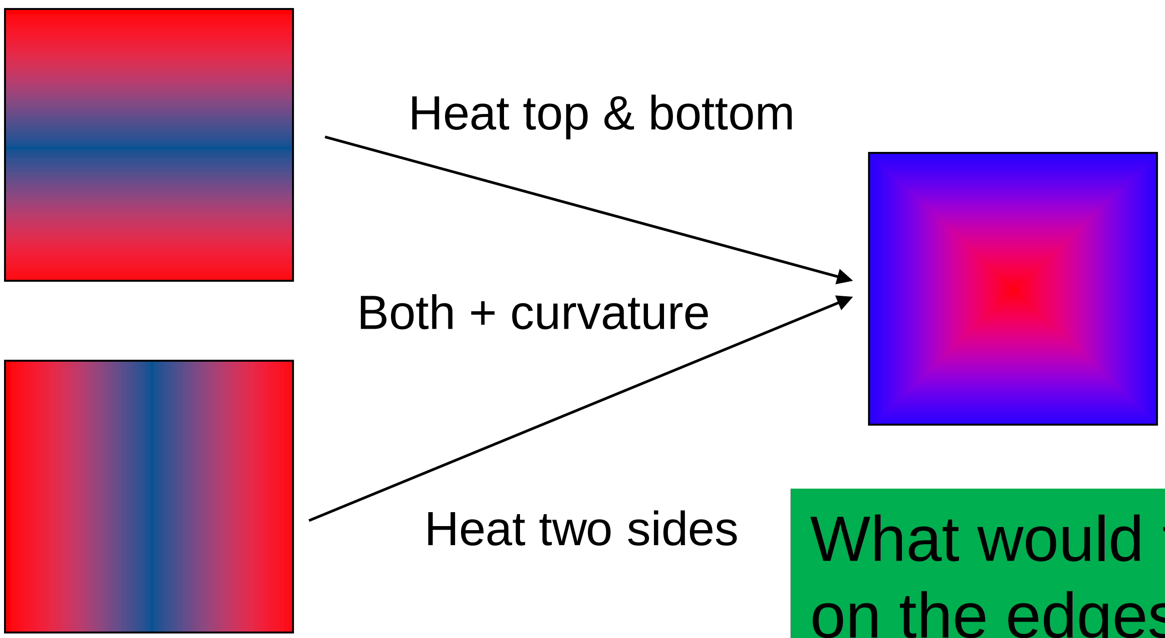


- Temperature fields that result in thermal strain that varies linearly do not add stress as the glass can deform to relieve strain.



Temperature profiles that add stress

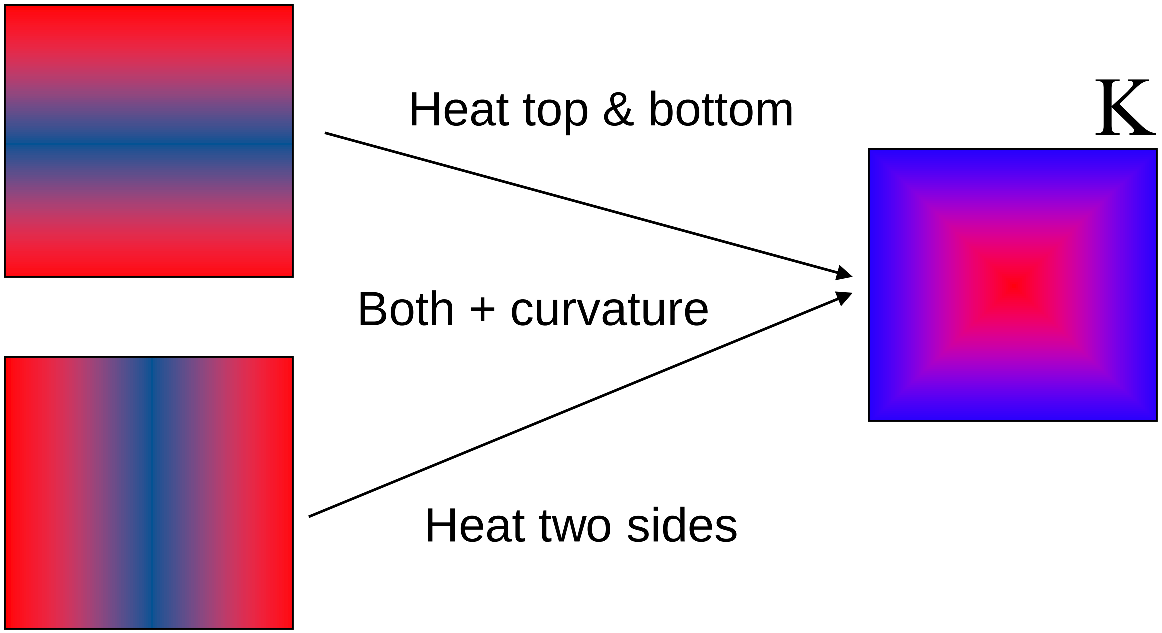
- Since linearly varying thermal strain does not add stress, stress comes from curvature in the thermal strain



What would the stress profile on the edges look like?

Temperature profiles that add stress

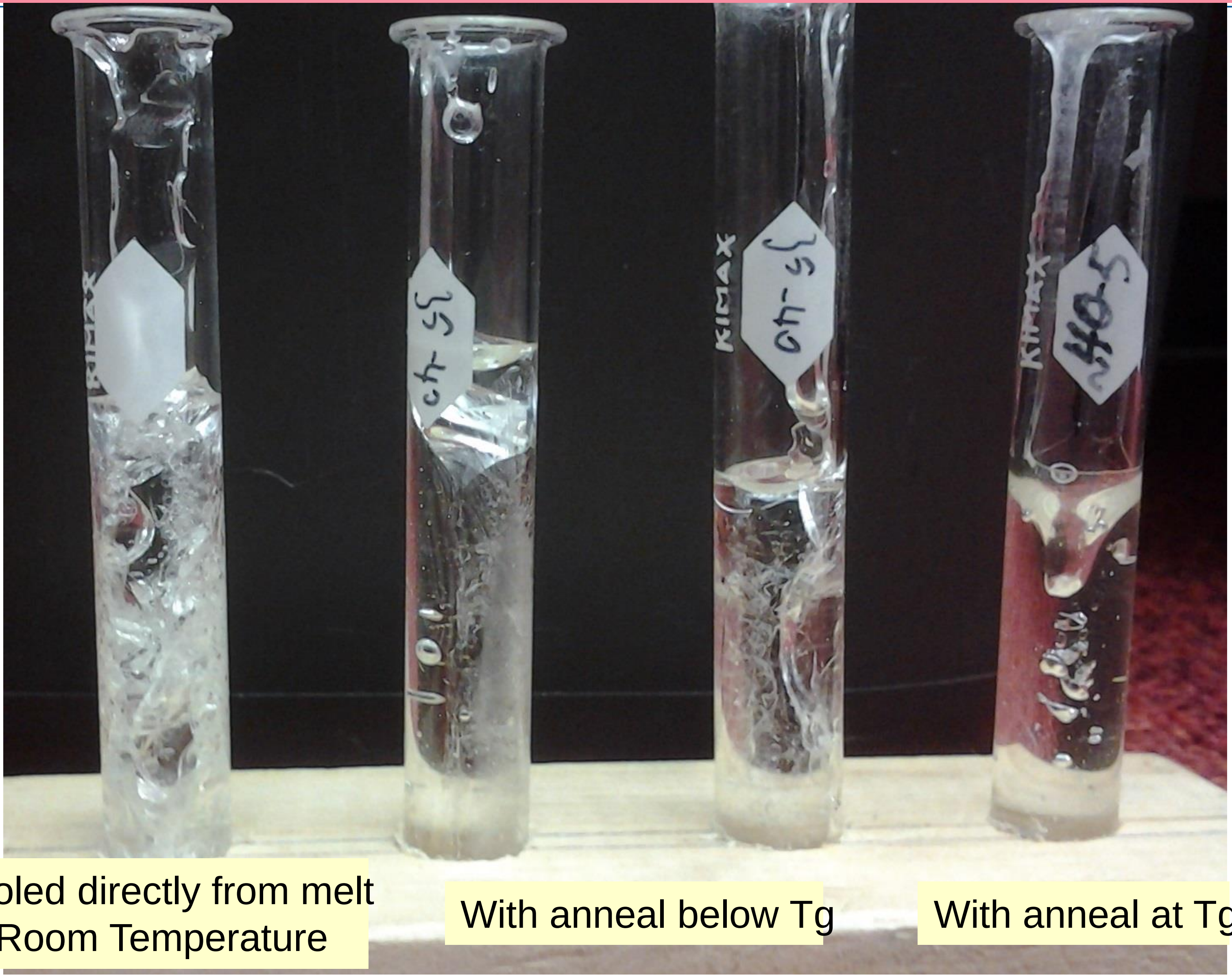
- Since linearly varying thermal strain does not add stress, stress comes from curvature in the thermal strain



$$K = \nabla^2 \varepsilon = \frac{d^2\varepsilon}{dx^2} + \frac{d^2\varepsilon}{dy^2}$$

$$\frac{d^2\varepsilon}{dy^2} = \frac{d}{dy}\left[\frac{d\varepsilon}{dT}\frac{dT}{dy}\right] = \frac{d^2\varepsilon}{dT^2}\left(\frac{dT}{dy}\right)^2 + \frac{d\varepsilon}{dT}\frac{d^2T}{dy^2}$$

Demonstration of Internal Stress in Glass and Importance of Thermal History – Sugar Glass cooled in Test tubes



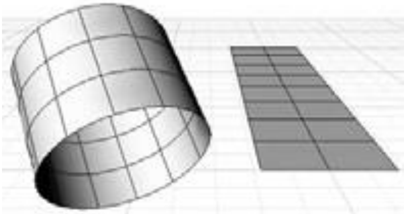
Cooled directly from melt
To Room Temperature

With anneal below Tg

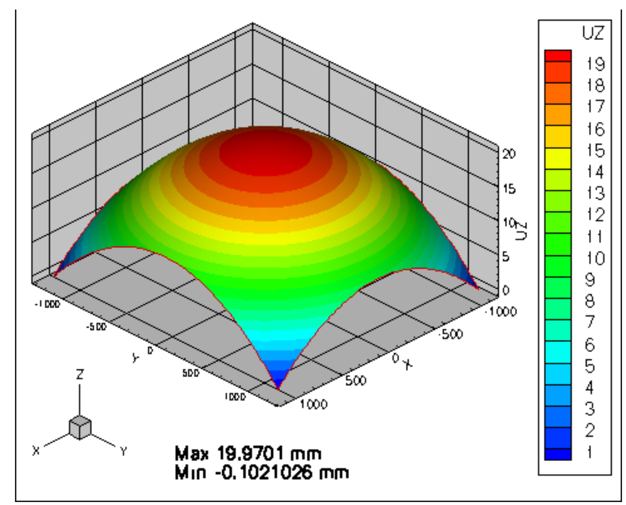
With anneal at Tg

A flat sheet also requires precise shape control

- Low shape and low stress glass enables multiple, high-res panels from a single sheet.
- Optimize ribbon forces that are both mechanically and thermally generated
- Flattening of large shapes creates stress
  - Why is large shape bad for a display device maker?



Make This!

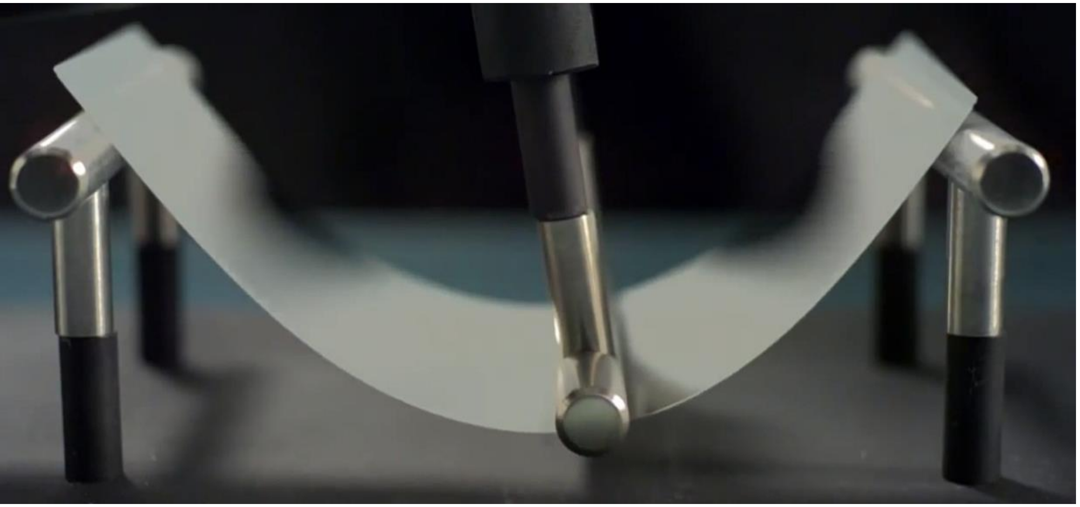


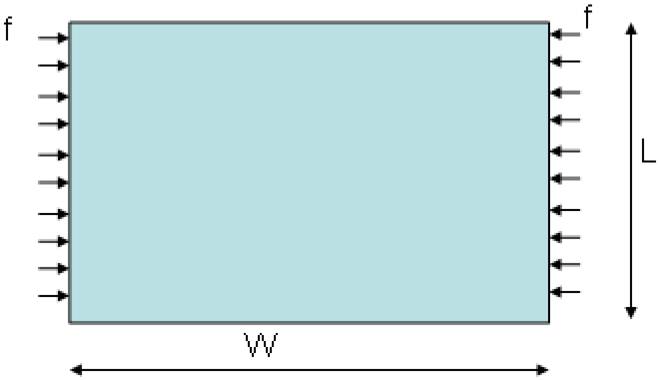
With thickness (thinness), other focus areas are identified

- Thin glass enables new frontiers, but also challenges glass makers and panel makers'

$$M = \frac{E\pi^2 h^3}{12(1-\nu^2)}\frac{1}{L^2}\left(a+\frac{1}{a}\right)^2, \quad \text{aspect ratio} \quad a \equiv \frac{W}{L}$$

H = Thickness
E = Modulus
L = length
W = Width





Using Fulcher's models helps us capture glass scaling relationships – integrate

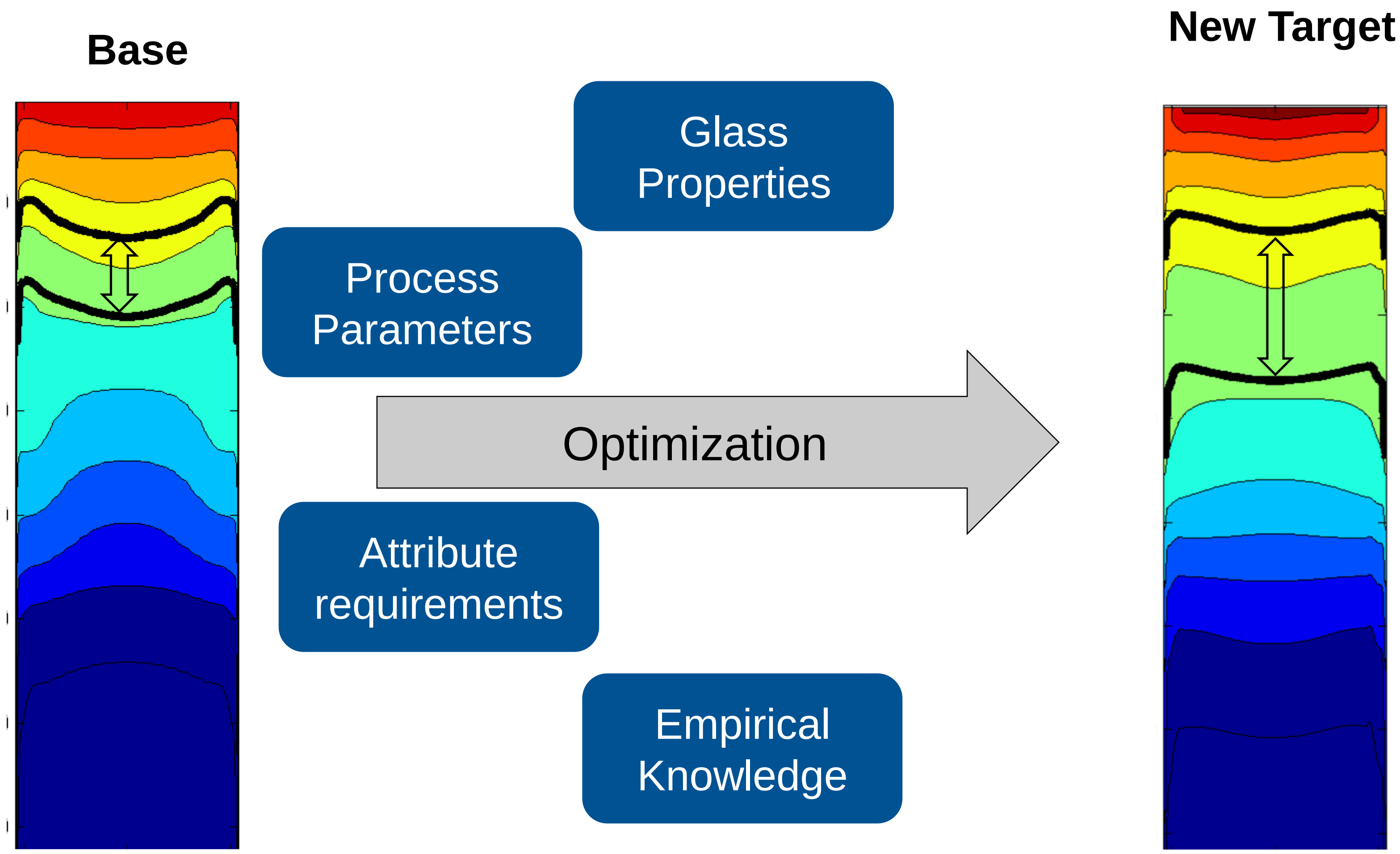
- Lets assume a glass with
  - A = -1.38
  - B = 3830
  - To = 288

$$Log(n) = A + \frac{B}{T - T_o}$$

- What is log(η) at 1000?

- log(η) can vary significantly with glass – process must be designed for this variance

Reliable glass making requires optimization on critical process elements



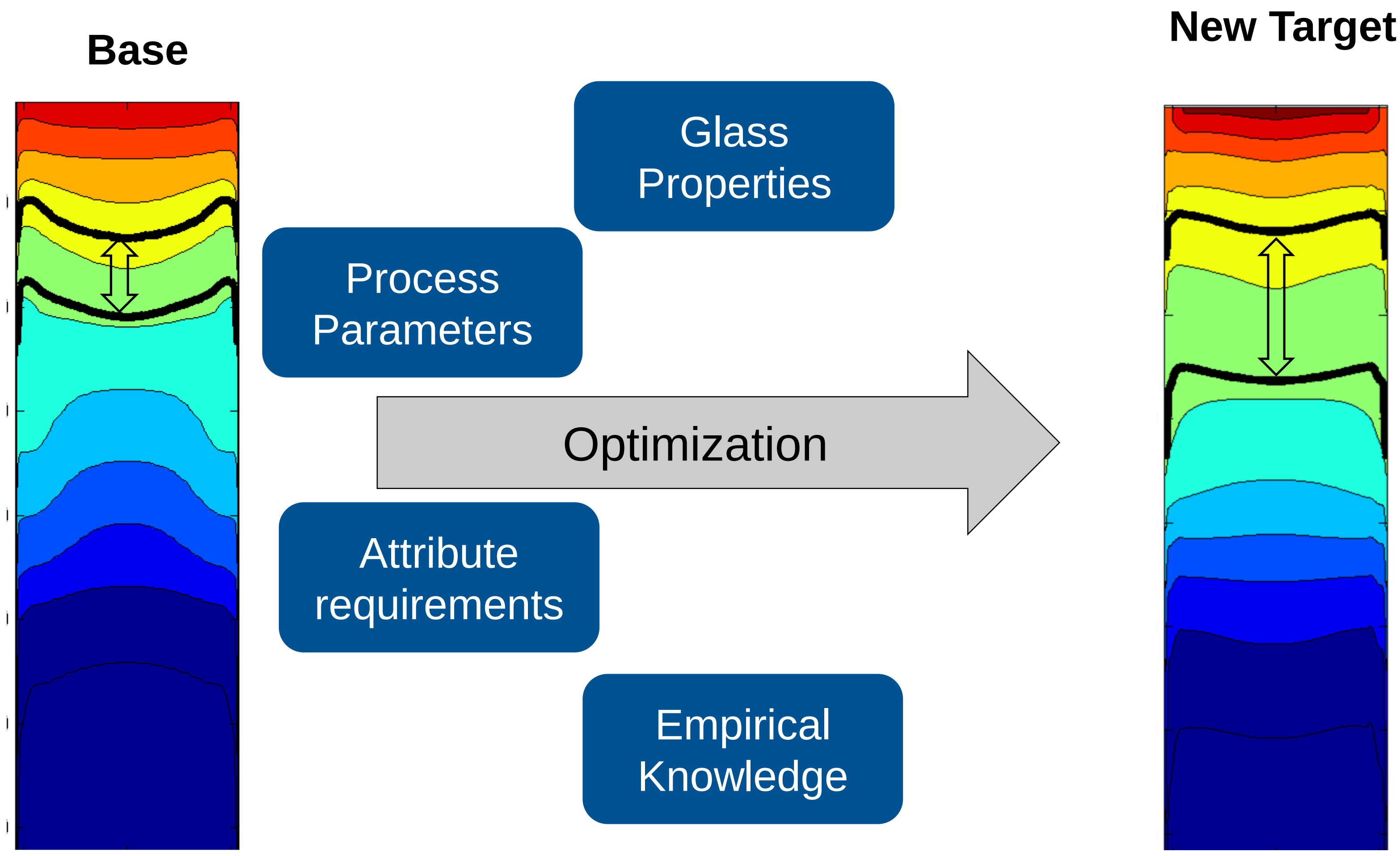
Successful forming developments requires use of multiple learning tools

- Deterministic system-wide solutions don't exist
  - Numerical modeling
    - Melt and Forming process design
  - Physical prototypes
    - Critical forming elements
    - Characterization and development of new materials

Designed experiments and statistical modeling help provide the holistic solutions

- Deterministic system-wide solutions don’t exist, physical modeling, and statistical models are critical to success
  - Numerical modeling
    - Melt and Forming process design
  - Physical prototypes
    - Critical forming elements
    - Characterization and development of new materials
  - Accurate Measurement technology
  - Advanced statistical models
    - Forming process design
    - Glass development
    - System models and predictor relationships
    - Parametric and surface response models

Numerical models, prototypes and advanced statistical methods are critical to fusion process development



In Closing

- The rapidly evolving markets drive high rates of change and innovation
  - Deep understanding of the fundamental sciences is necessary
- Glass forming covers large viscosity ranges, and each application must be uniquely optimized for performance
  - No single method provides all the answers and we must develop skills across processes and learning tools
- Glass making is a journey that combines sciences and artistry and requires resilience

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