Fate of a Broken Space Elevator

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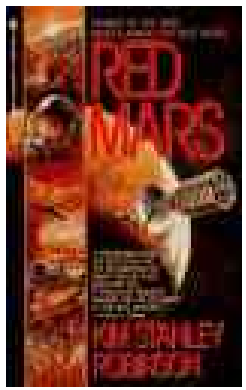
Some Previous Work

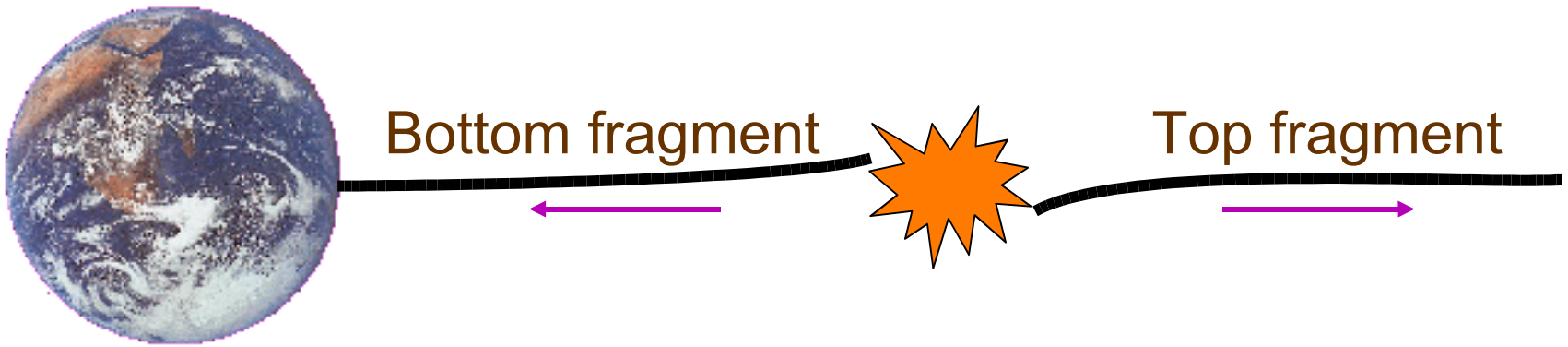
- **Tower of Babel**
  - Don't mix inches and meters.
- **Kim Stanley Robinson's Red Mars**
  - Falling space elevator is a cataclysmic event.
  - Wraps around Mars multiple times.
  - Hits hard, with destructive violence.



- **Dr. Bradley Edwards**
  - Broken ribbon flutters to the ground or burns up.
  - Top fragment might be reattachable.

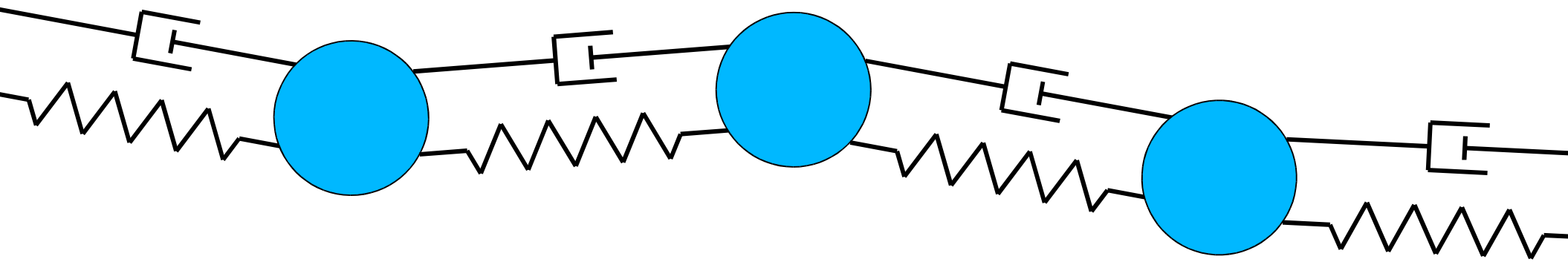
Single Break Model

- **We consider a failure where the elevator breaks at a single place.**
- **Two fragments result, we study each one independently.**



The Simulator

- **Ribbon:** strength 130 GPa, Young's modulus 1 TPa, density 1300 kg/m², uniform stress of 65 GPa.
- **Breaks:** if strength exceeded or reenters too fast.
- **Simulation:** written in C, rotating reference frame, 100 masses and springs, forward Euler integration, 1 s time step, heavy longitudinal damping.

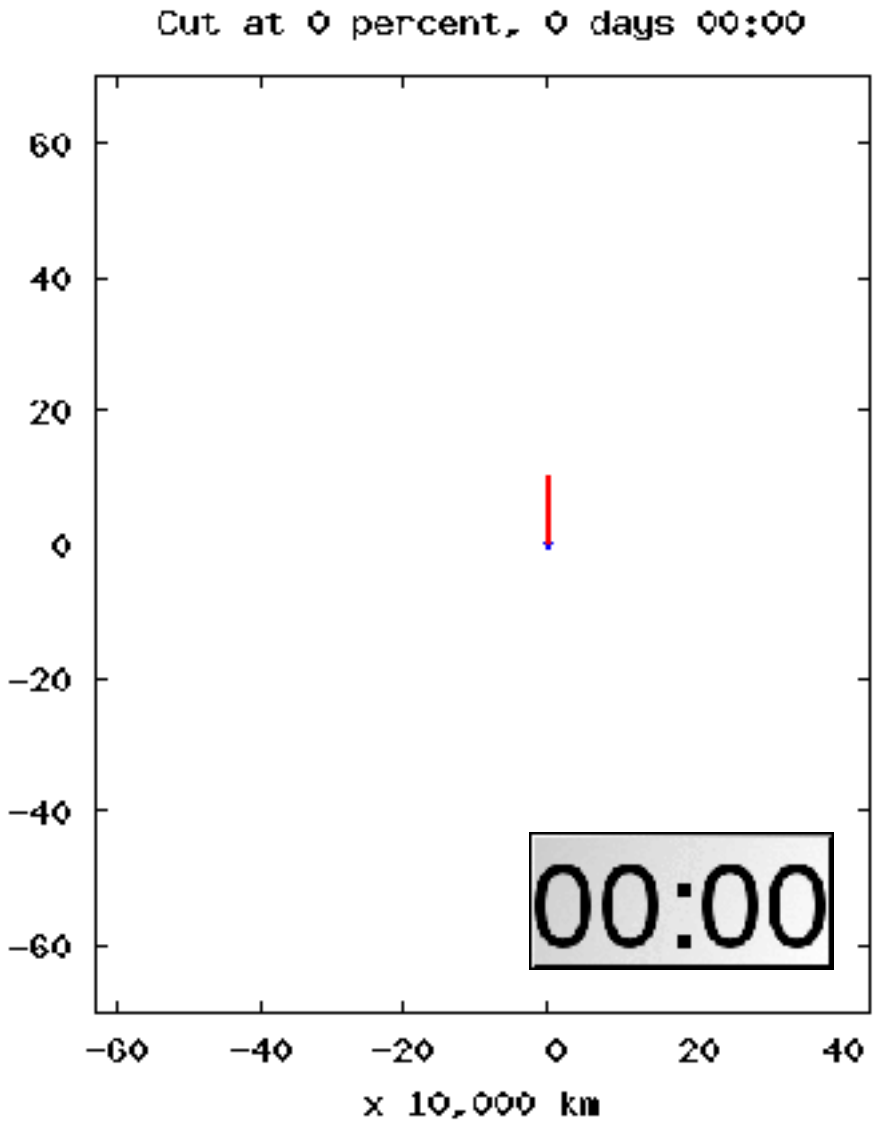


Outline

- **Introduction**
- **Top Fragment**
- **Bottom Fragment**
  - Simulations
  - Reentry Modeling
  - Effect on Ground-Based Assets
- **Collisions in Space**

The Top Portion Escapes

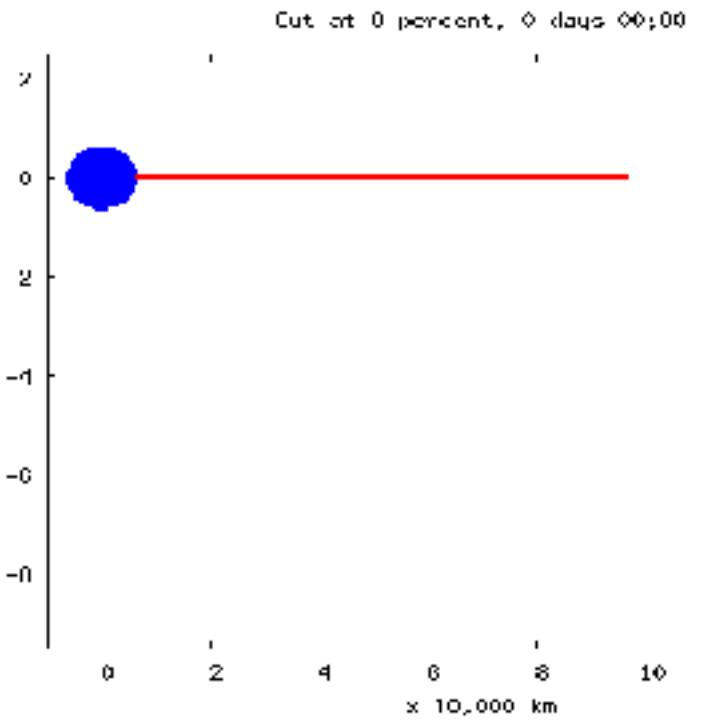
- The top fragment of the elevator always escapes from the Earth.
- Recovery seems very improbable.



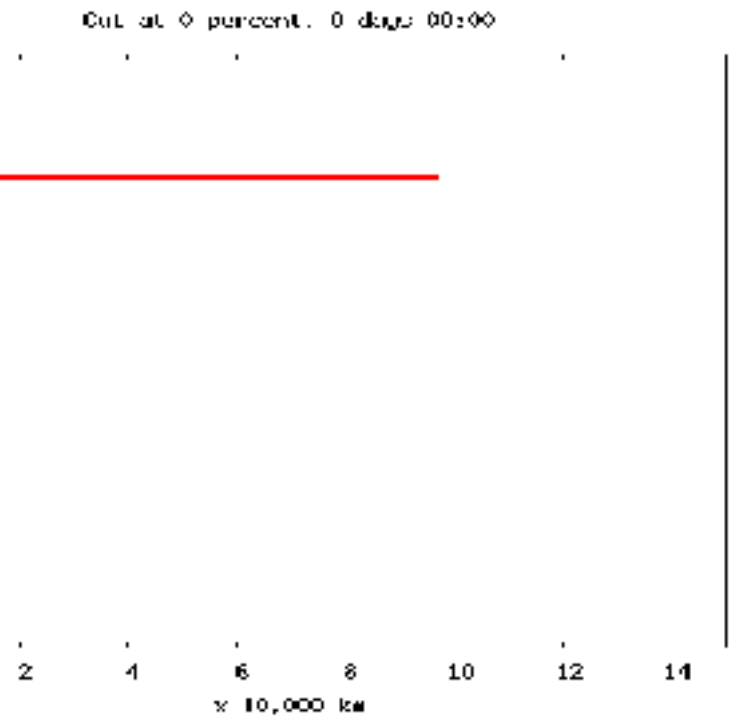
Effect of a Climber

- **Even with a climber at its base, the top fragment escapes.**
- **Moving climbers around will not help.**

Without Climber



With Climber



Stability of Unanchored Space Elevator

- **Arnold and Lorenzini (1987): A long enough dumbbell tether has positive orbital energy and is unstable.**
- **Steindl and Troger (2005): A geo-synchronous sky hook is unstable.**
- **Impact for space elevator:**
  - When elevator is anchored, there is no stability problem.
  - Risk of stability problems when you are finished deploying but before you anchor?
  - Deployment increases stability.
  - How fast do you need to deploy to be stable?

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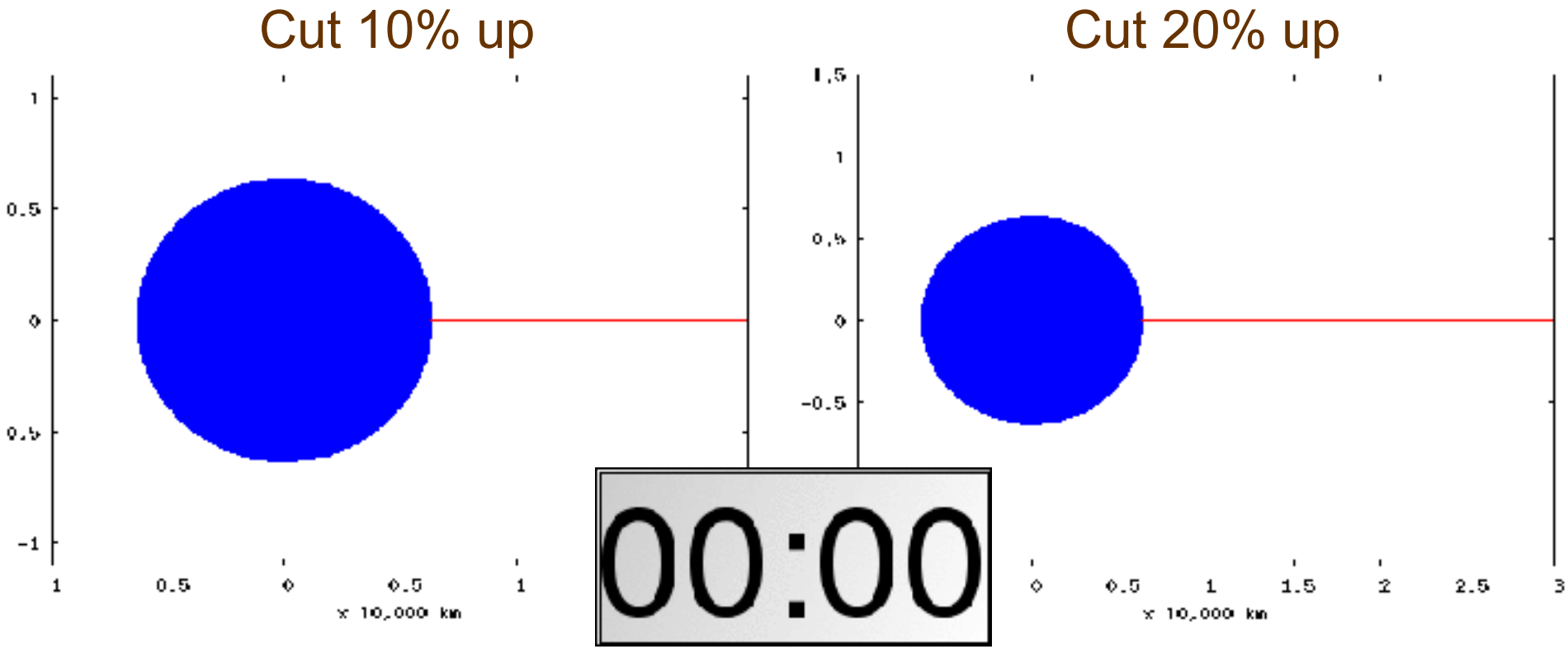
Low Breaks

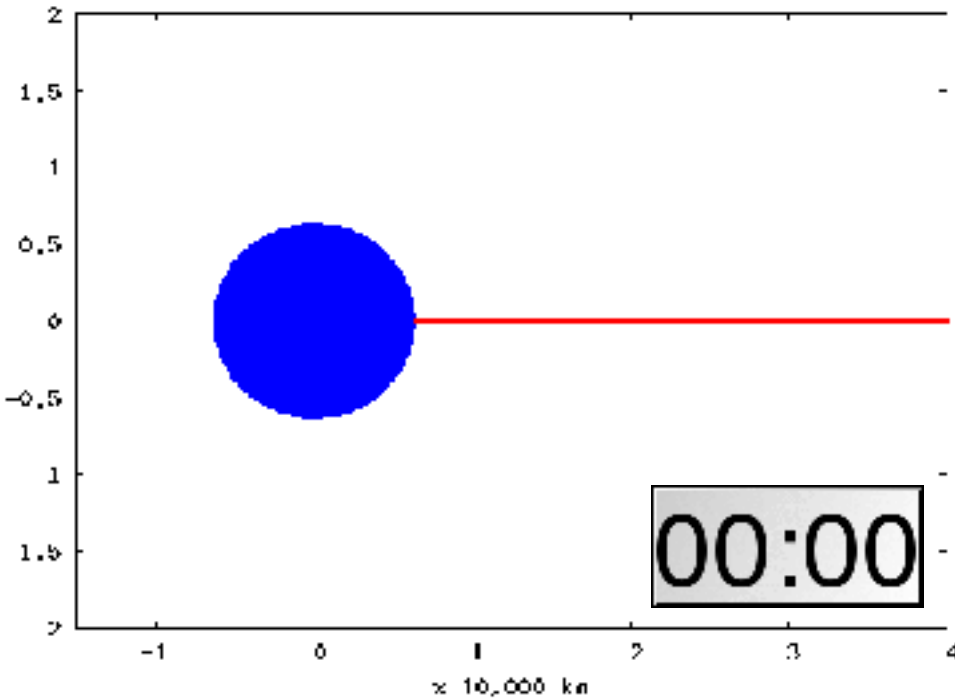
- **Most likely case (LEO).**



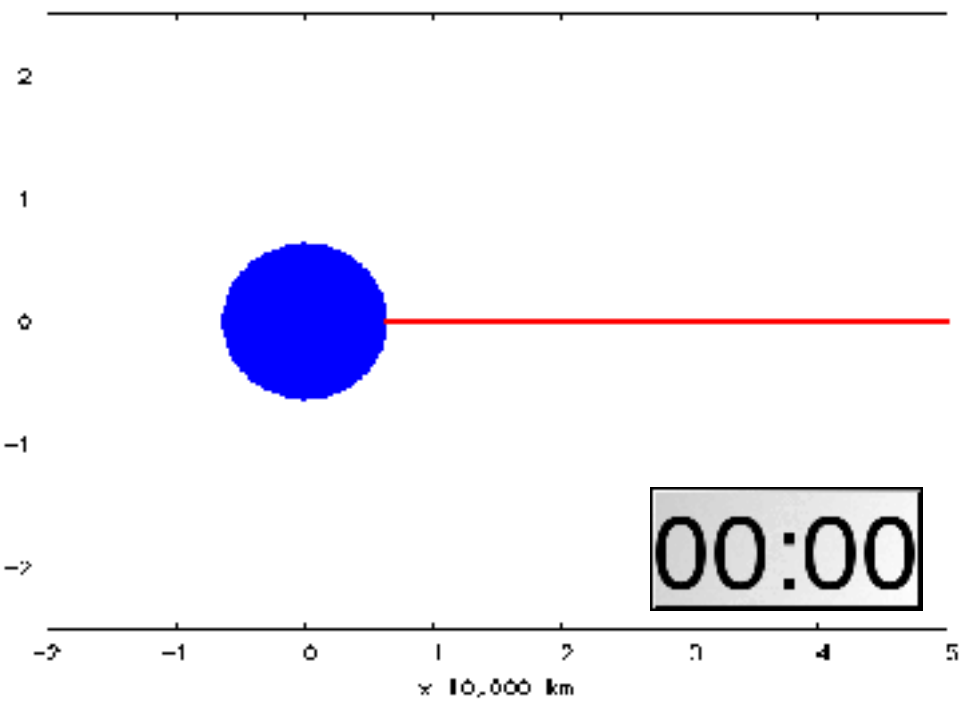
- **Minimal Coriolis effect. Falls straight down.**
- **Some burnup on reentry.**

Breaks near GEO

Cut 30% up



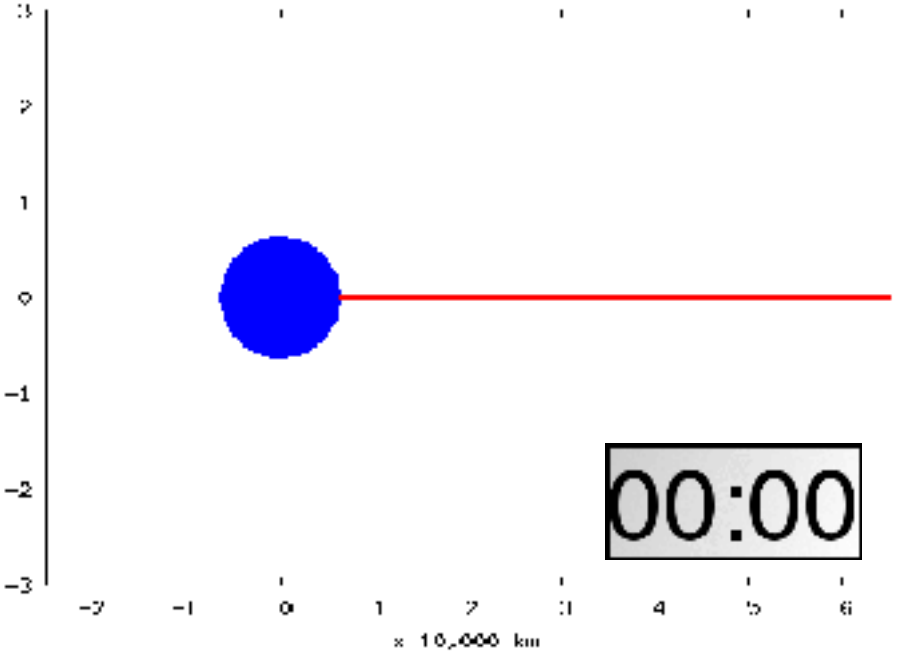
Cut 40% up



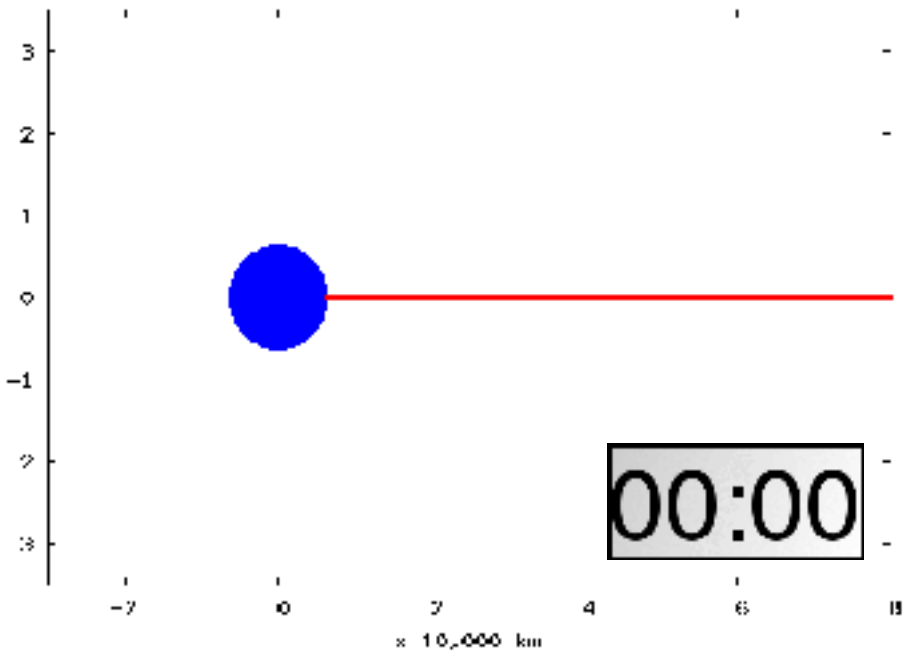
- Significant **wrapping** around Earth.
- **Burn-up** can cause fragments to be **flung away**.
- Example of **long lived fragment** in 30% case.

Higher…

Cut 50% up



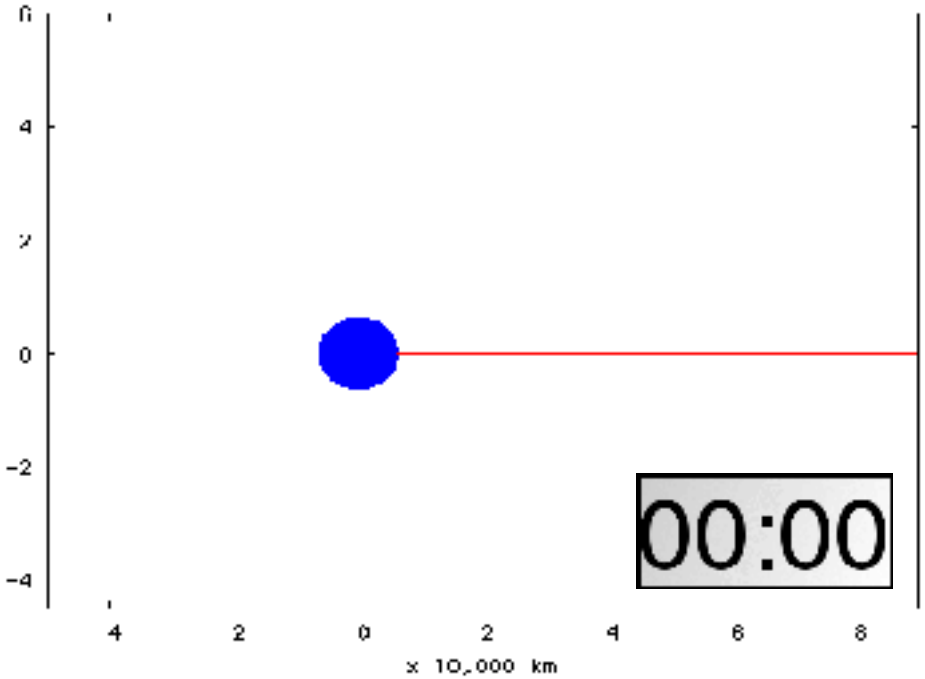
Cut 60% up



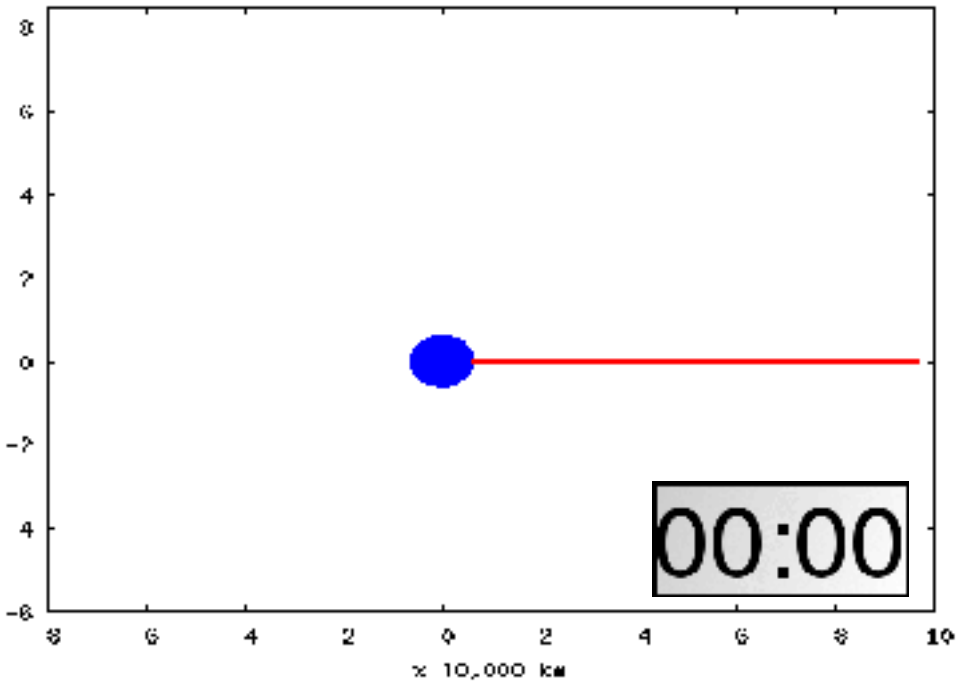
- **Centrifugal force causes first break now.**
- **Tip of ribbon whips around sporadically.**

Near the tip

Cut 80% up



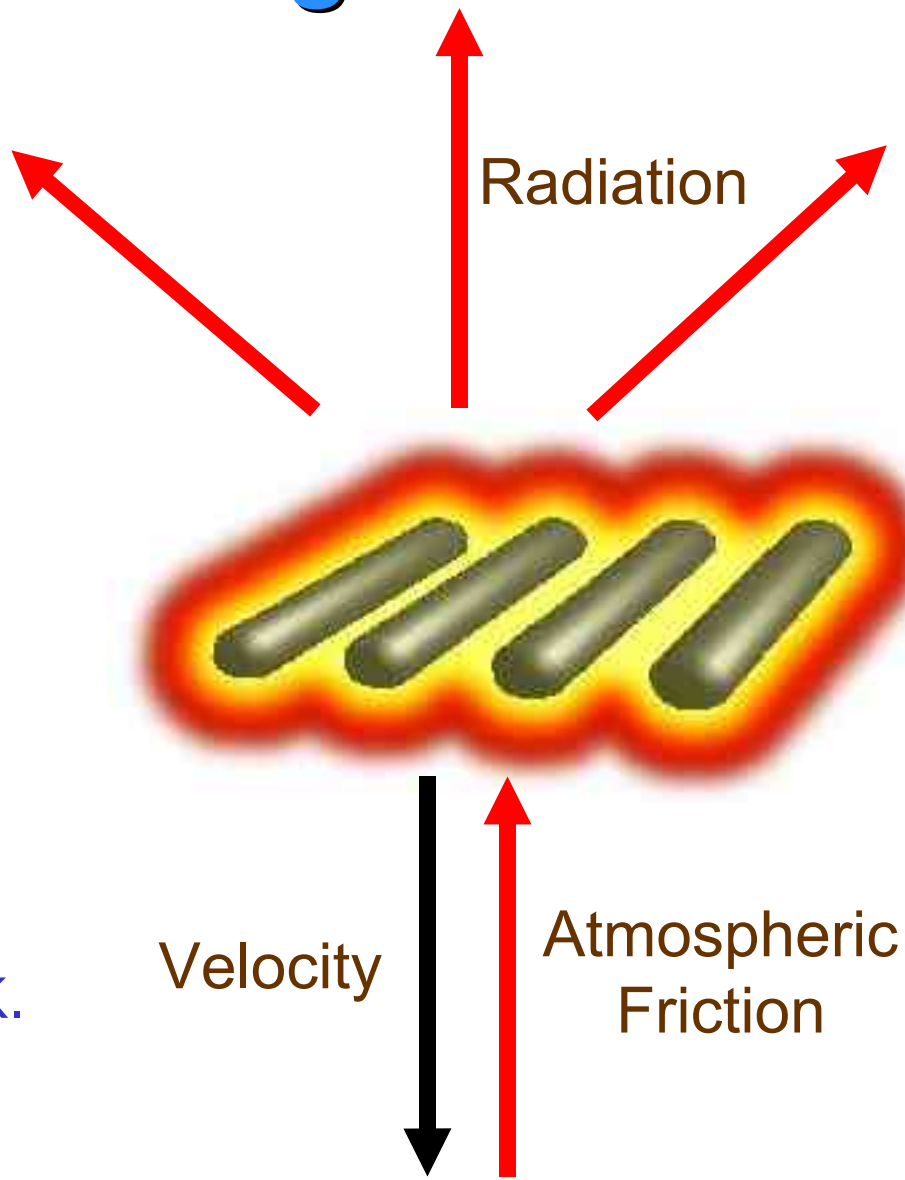
Cut 100% up



- **Wraps all the way around the Earth.**
- **Overall small fraction of ribbon burns up**
  - Worst case for break 30% up ribbon.

Reentry Modeling

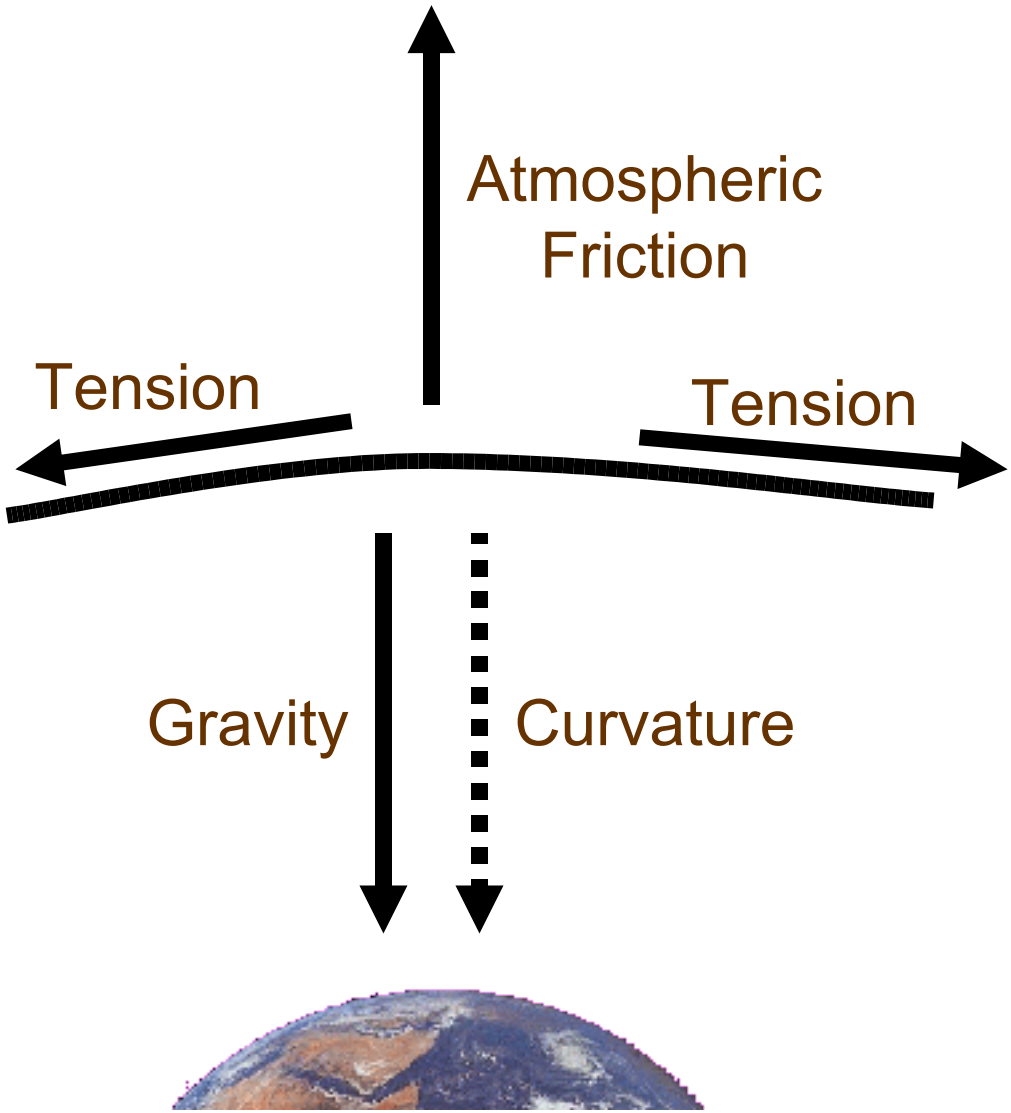
- **Based on models for meteoroids.**
  - Jones and Kaiser (1966)
- **Ribbon threads are very thin (10 m).**
  - No thermal mass
  - Uniform thread temperature
- **No ablation for slow enough reentry.**
  - Assume ribbon ablates at 600 K.
  - Limit velocity ≈ 5 km/s.



Terminal Velocity

- **Simulation shows situation at start of reentry.**
- **After initial reentry, slows to terminal velocity.**
  - 10 m/s at 43 km
  - 0.5m/s at ground level

⇒**Impact of elevator is leisurely.**

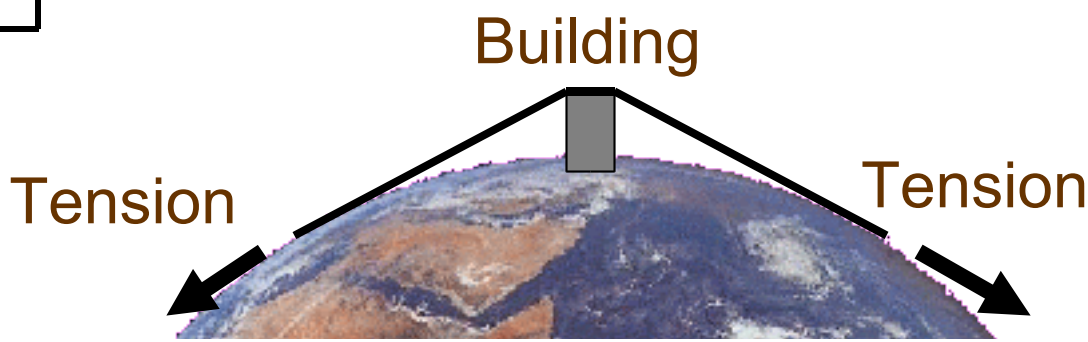


Force on Ground Object

- **Once ribbon reaches ground, only curvature force can be large.**
  - Worst case for large building with clear path to horizon.
  - Force arises from change in direction of tension.
  - For 20 T elevator:

Height	Force	Force/Width
1 m	1.1 kN	1 kN/m
100 m	11 kN	10 kN/m

- **What about slipping/ sawing?**



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Bottom Fragment

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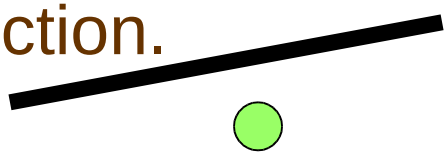
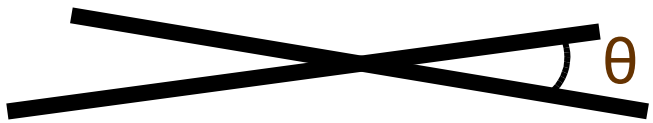
Collisions in Space

- **Assume any collision is bad.**
- **Usually small risk window**
  - A few hours for top fragment.
  - A day for bottom fragment.
- **Fragment with Satellite**
  - Small collision cross-section.



  - Comparable risk to normal operations except GEO satellites.
- **Fragment with Elevator**
  - Large collision cross-section.



  - Significant risk during limited period of time.

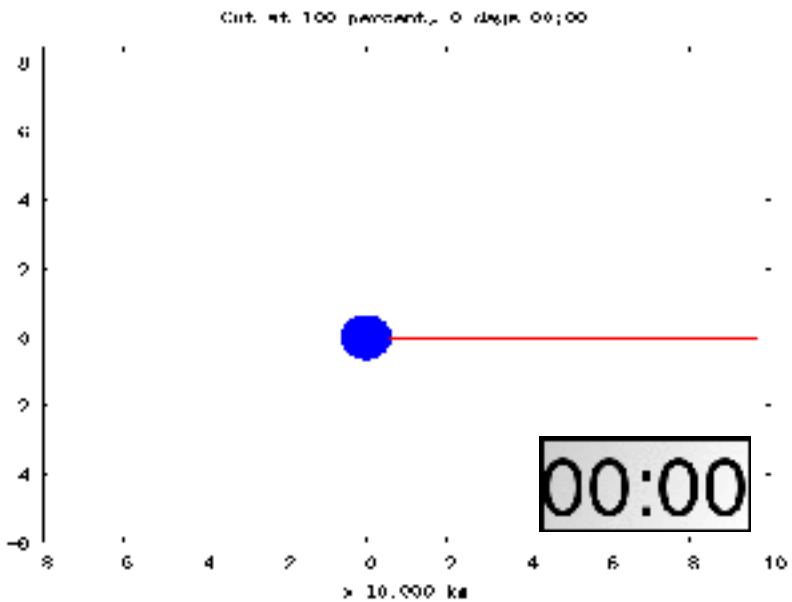
Limiting Risk to Elevators

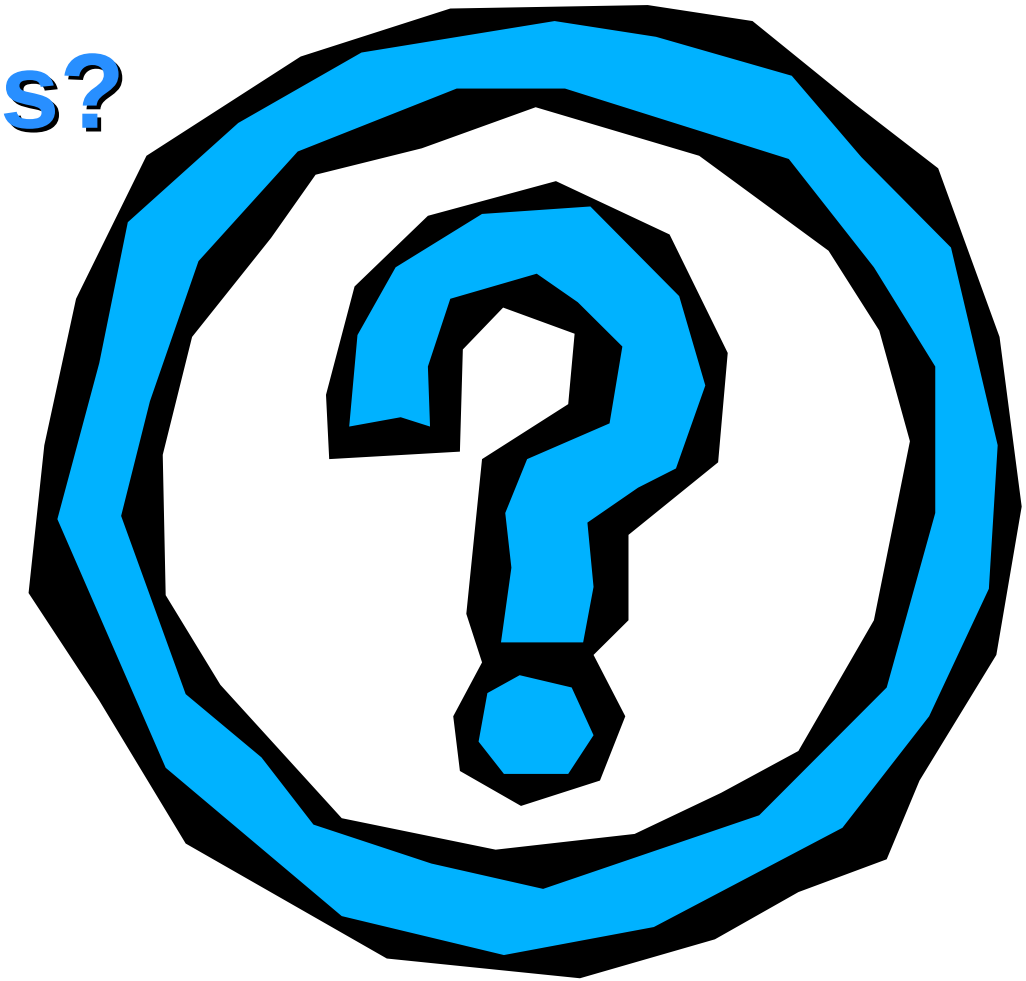
- **Only ever deploy a single space elevator**
  - Allows rolled up elevators to be in space for recovery.
  - Not a very compelling solution in the long term.
- **Space out elevators by 90 degrees of longitude**
  - Works for low-altitude breaks.
  - At most 4 elevators.
- **Move off equator if break occurs**
  - Needs detailed study to confirm reliability.

Conclusion

- **Confirms Brad Edwards' reassuring views.**
  - Falling ribbon poses no mechanical threat at ground level.
  - Smaller risk of elevator fratricide than feared.
- **Some surprises**
  - Recovery of top fragment is not an option.
  - Less ribbon than expected burns up.
- **Future work**
  - Look into stability issues for unanchored ribbon.
  - Better models for the simulation.

Questions?





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