Workshop on Dynamic Locomotion and Manipulation
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Skippy: Reaching for the Performance Envelope

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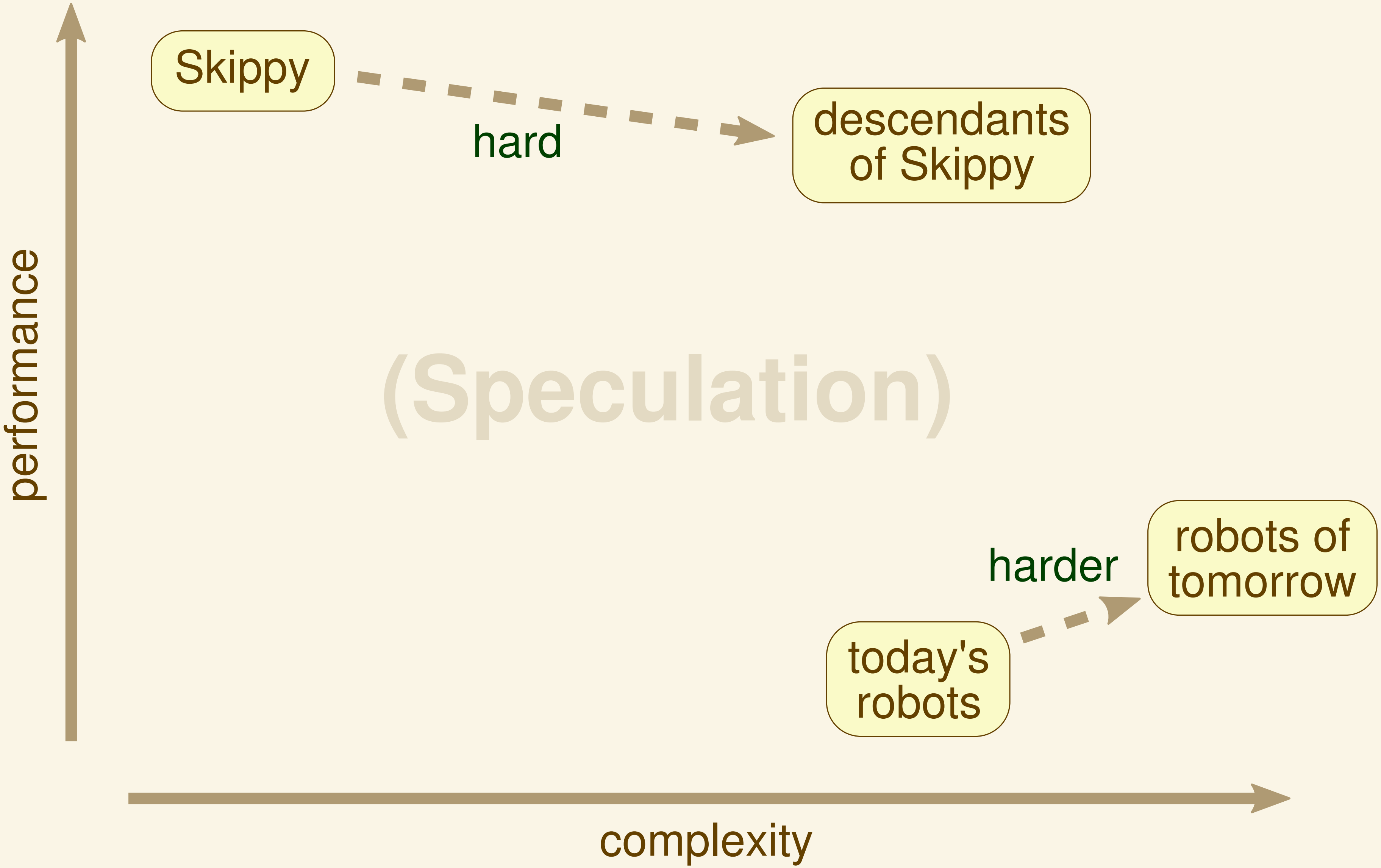
What is Skippy?

- a hopping and balancing machine
- an attempt to achieve far higher physical performance than today's robots
- an attempt to test the following hypothesis:

  It is easier to increase the complexity of a high-performance robot than to increase the performance of a highly complex robot.

What is Skippy?



What is Skippy?

A robot that is/has

- fully autonomous — no umbilical or harness
- light weight — ~2kg
- only 2 actuators — maximally simple
- energetic — 4m hop
- robust — crash land from 4m without damage
- versatile — balance, bow, swivel, hop, somersault, tumble, dance, pirouette, climb stairs, fall over and get back up again, ...

What is Skippy?

Why hopping and balancing?

1. because they are foundational skills for an athletic robot

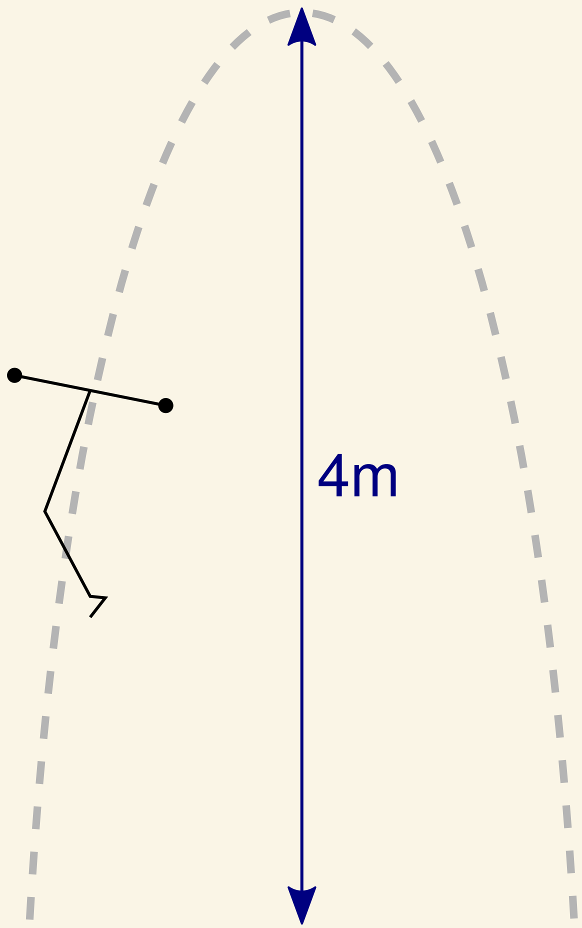
2. because they enable many other skills

3. because they have very different (and conflicting) requirements, so the robot must be *versatile* if it is to be good at both

hopping needs explosive power

balancing needs exquisite control

Specification: Hopping

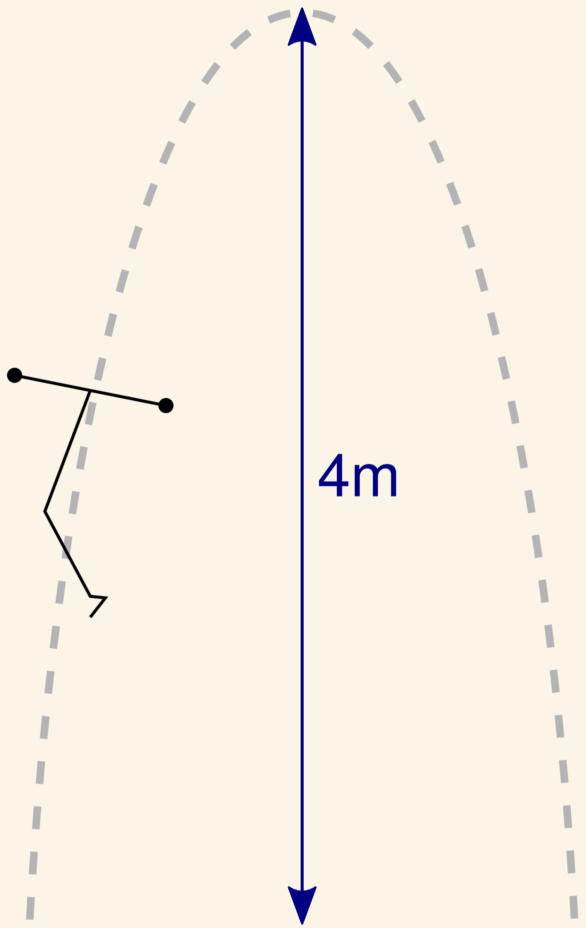


- Skippy must be able to hop 4m and land on its foot, or crash without damage
- Up to 50% of the required energy can come from the previous hop

Why 4m?

- because it's outrageous
- because it's spectacular
- because it's possible
- because it pushes the limits
- because it focuses attention on physical performance

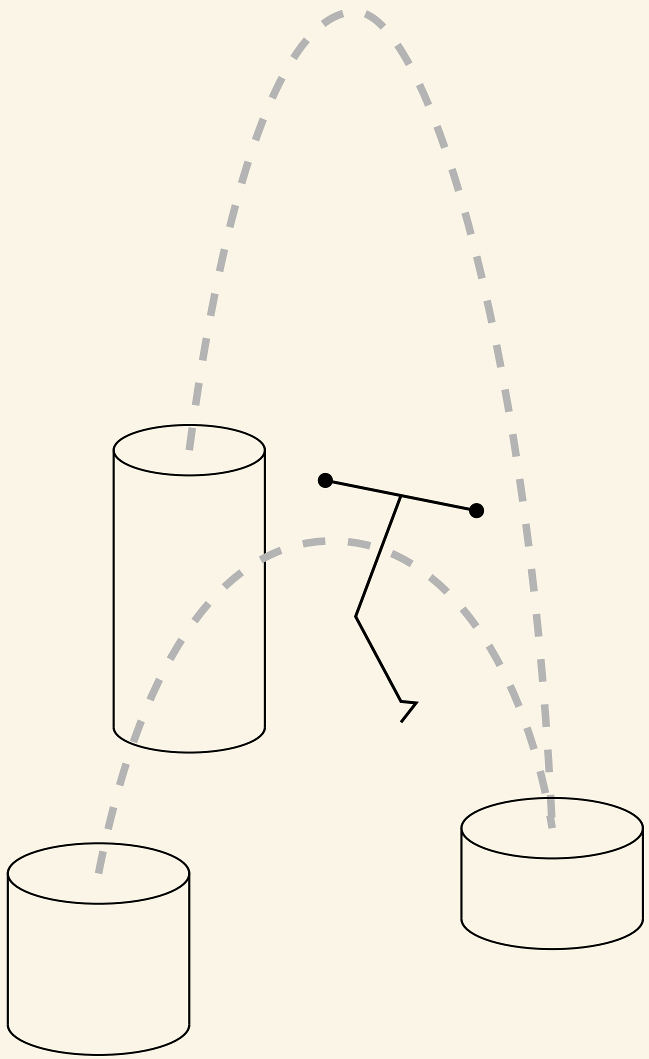
Specification: Hopping



Some numbers:

- 2kg @ 4m = 80J
- 4m hop → 9m/s launch velocity
- 9m/s → 1.8s flight phase
- 9m/s @ 0.5m stroke
  → 0.2s stance phase (10% duty cycle)
  → 9g average stance acceleration
  → 200N average thrust
- if 40J from previous hop then
  → 200W average stance power

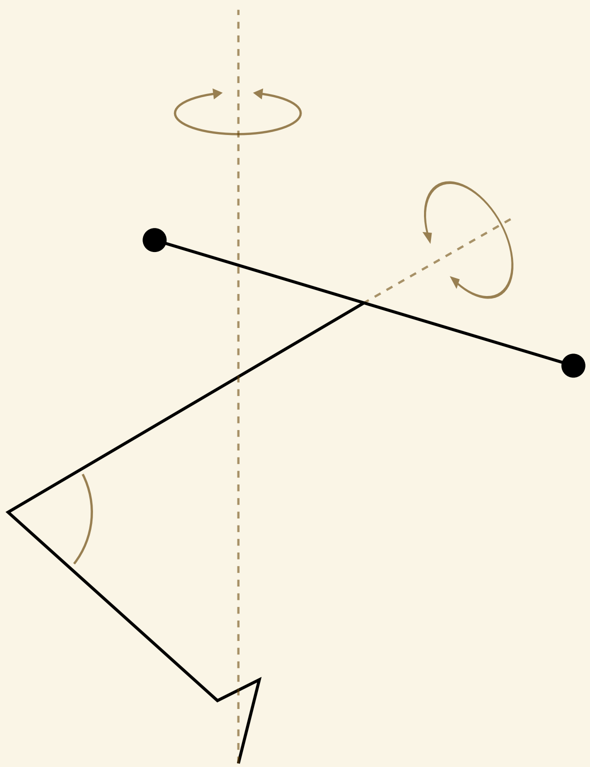
Specification: Hopping



Skippy must also be able to make

- small hops
- single hops
- hop sequences
- precisely targeted hops
- hops off inclined surfaces
- modified hops (somersaults, etc.)

Specification: Balancing



Skippy must be able to

- balance on a point in 3D
- balance while making large fast movements
- balance quickly on landing
- lean in preparation for a hop
- control all three posture angles
- control attitude during flight
- control foot placement on landing

(Skippy must also be able to get up by itself after a fall)

Normal Robotics Research

Step 1: create a robot that is

- very complex
- very expensive
- very fragile/self-destructive
- very heavy
- barely strong enough

Step 2: perform experiments

- very cautiously
- at low speeds
- hampered by complexity, risk management, frequent failures, repairs, poor performance, ...

The Skippy Approach

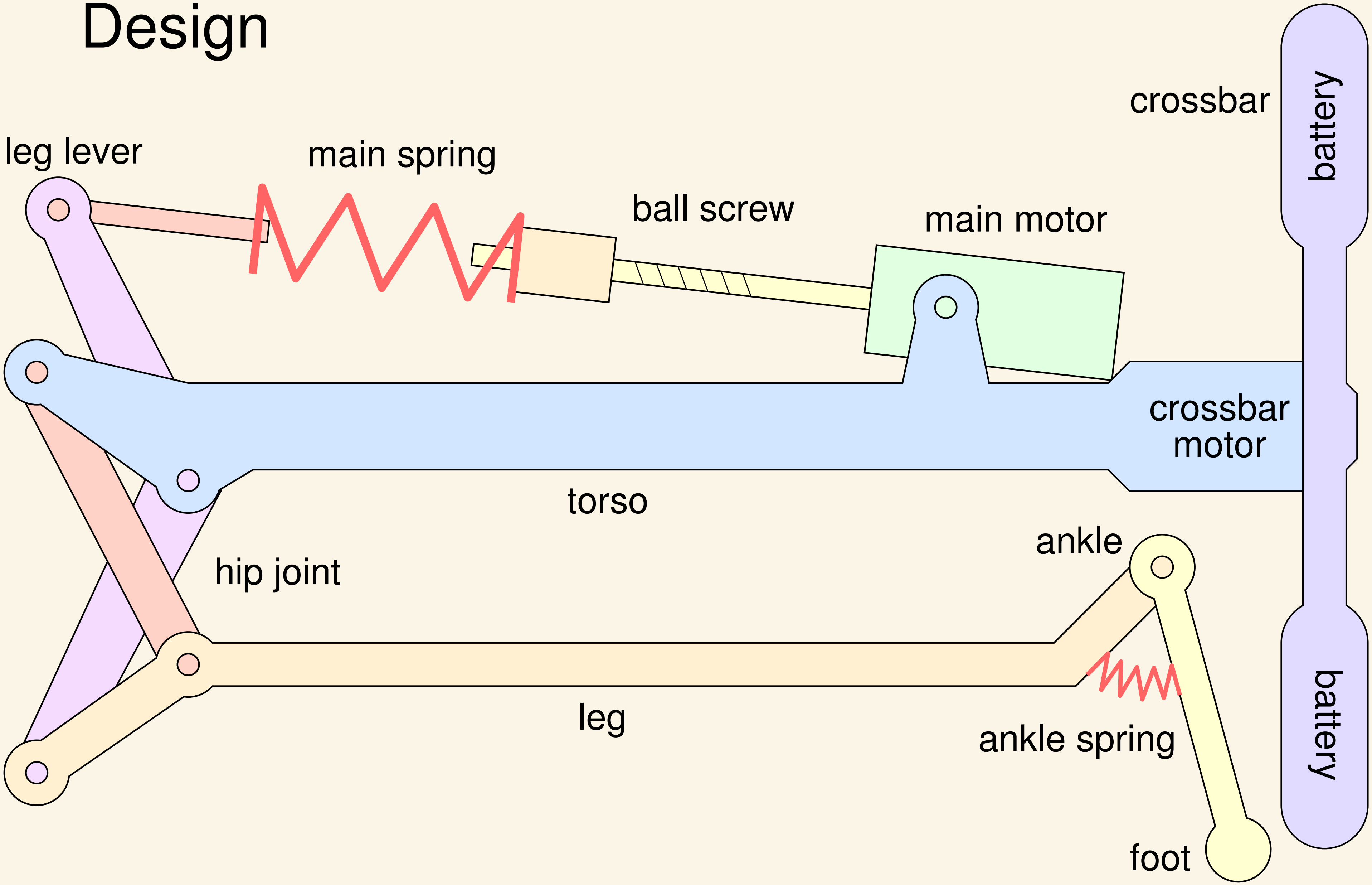
Step 1: create a robot that is

- maximally simple
- relatively cheap
- robust/non-self-destructive
- light
- highly energetic

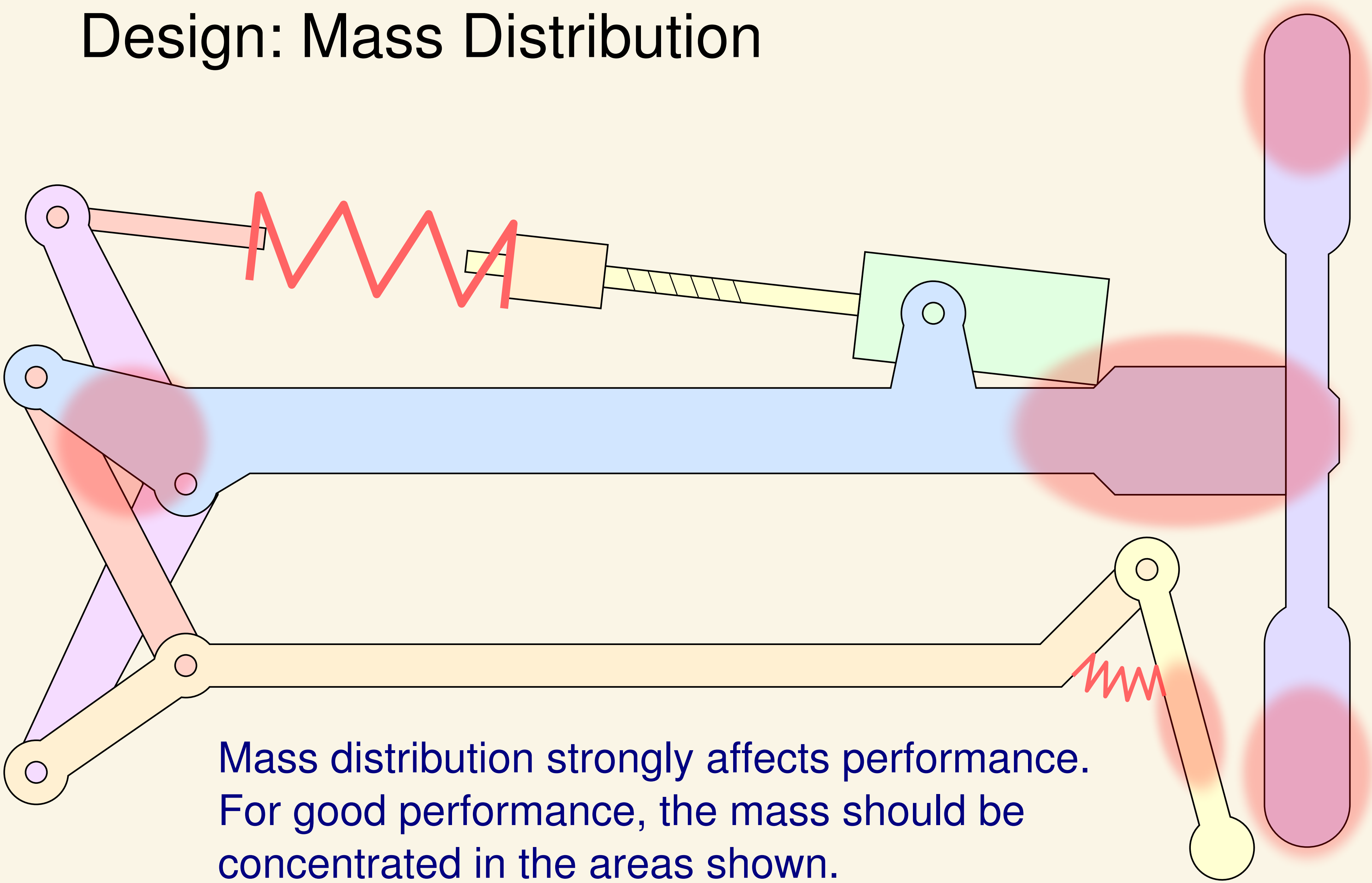
Step 2: perform experiments

- aggressively
- safely at high speeds
- making rapid progress and discovering new things

Design

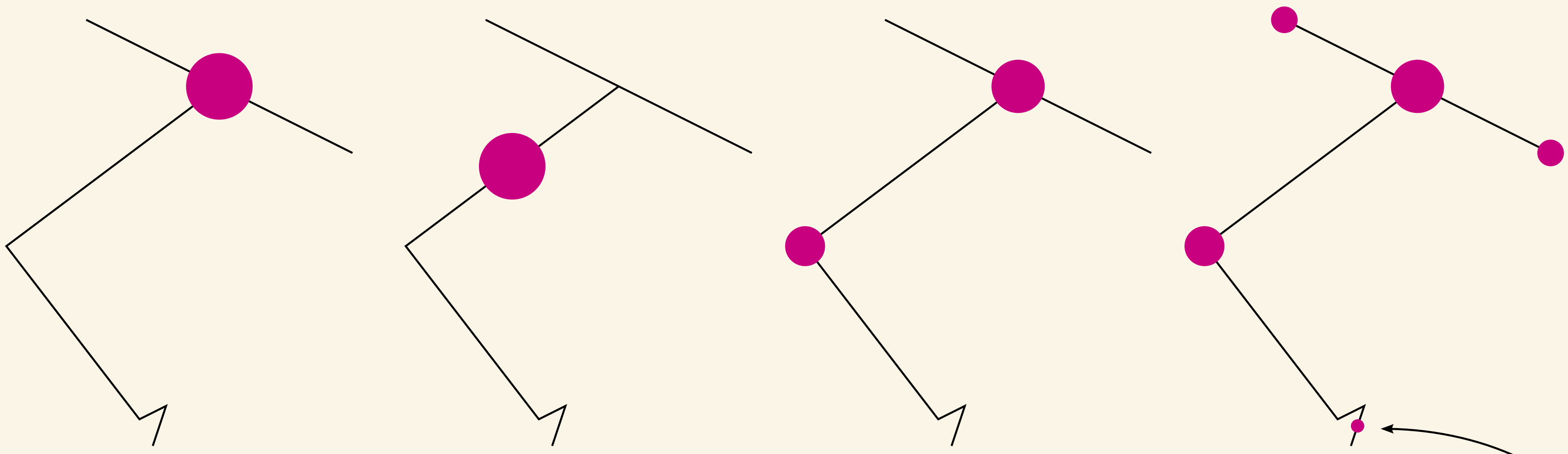

leg lever
main spring
ball screw
main motor
crossbar
battery
crossbar motor
torso
hip joint
ankle
leg
ankle spring
battery
foot

Design: Mass Distribution



Mass distribution strongly affects performance.
For good performance, the mass should be
concentrated in the areas shown.

Design: Mass Distribution



excellent hopper

bad balancer

OK hopper

bad balancer

good hopper

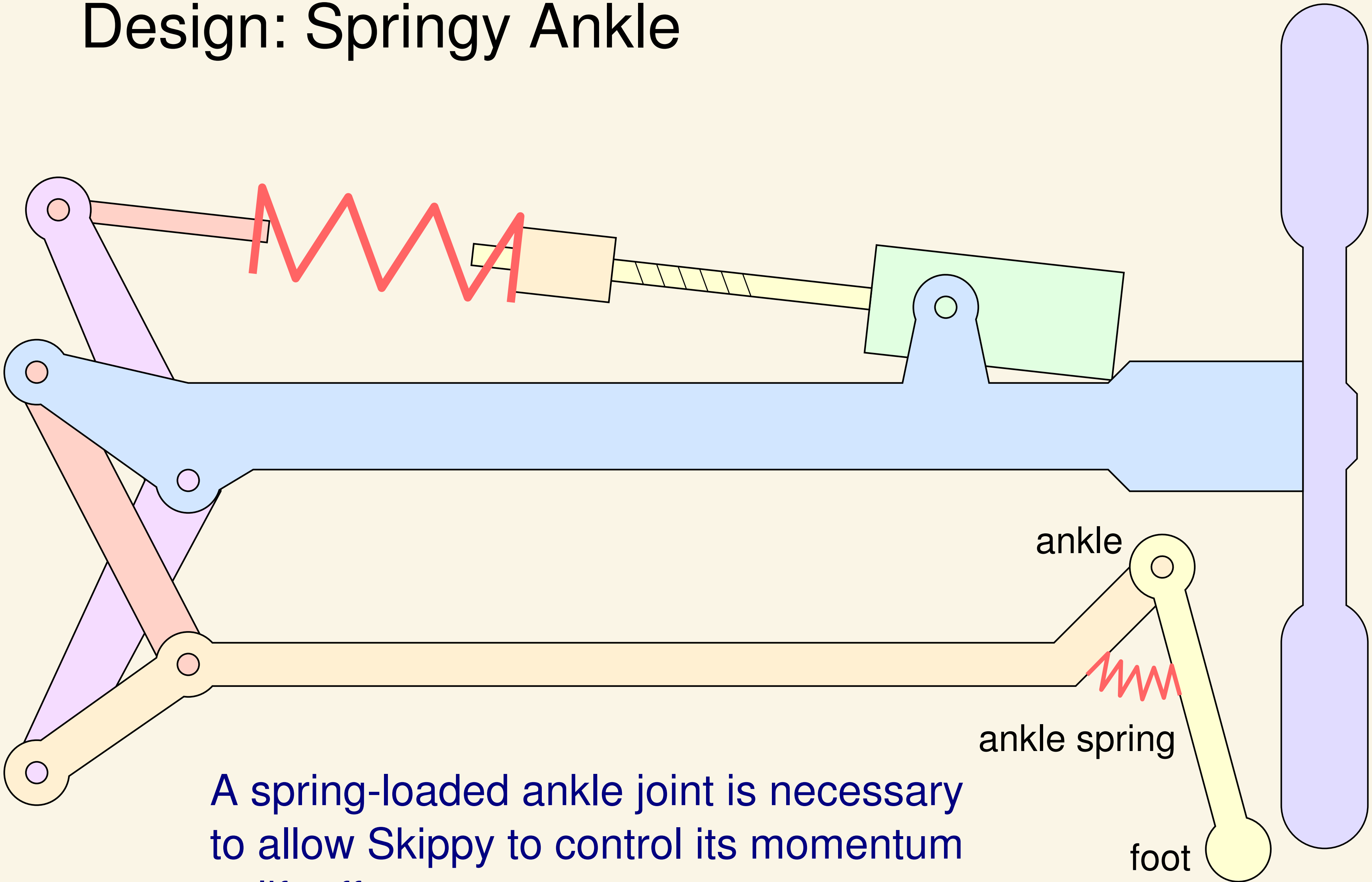
good 2D balancer

good hopper

good 3D balancer

plus some mass at the foot for in-flight attitude control

Design: Springy Ankle



A spring-loaded ankle joint is necessary to allow Skippy to control its momentum at lift-off

Design: Springy Ankle

A hop is essentially a planar movement taking place in the robot's saggital plane.

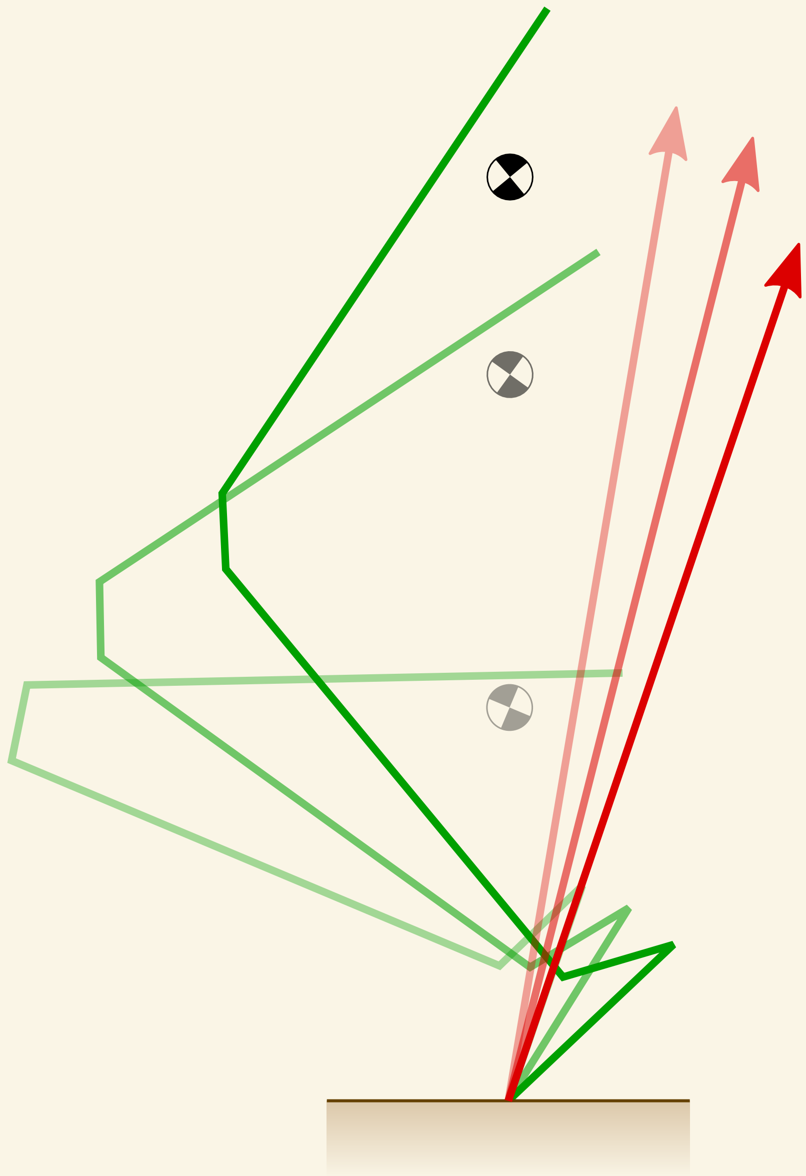
To control all three components of momentum in this plane using only a single actuator, it is necessary to divide the launch phase into a *thrust phase* and a *steering phase*.

thrust phase: the main motor is saturated and operating at maximum power

steering phase: the springy ankle allows the main motor to control the direction of ground reaction force

Design: Springy Ankle

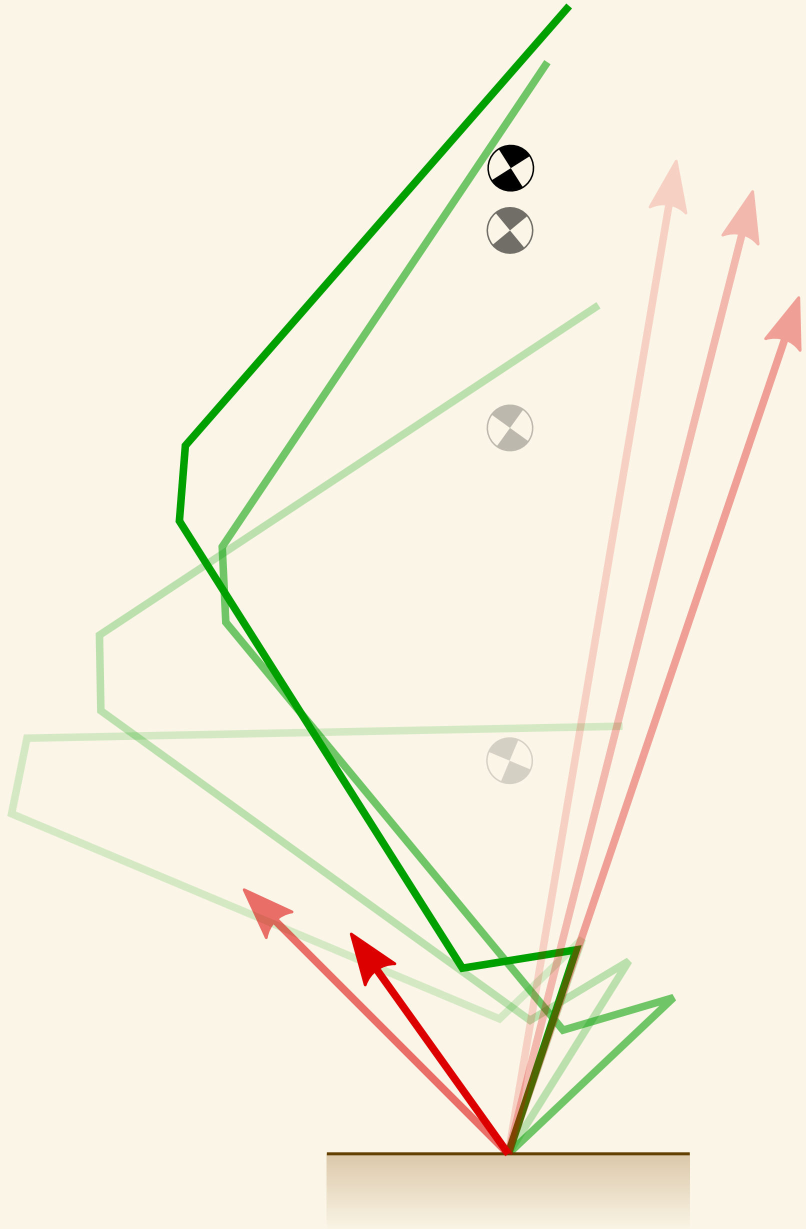
During the thrust phase, the ankle *remains flexed*, and the ground reaction forces exert a *positive* moment about the CoM.



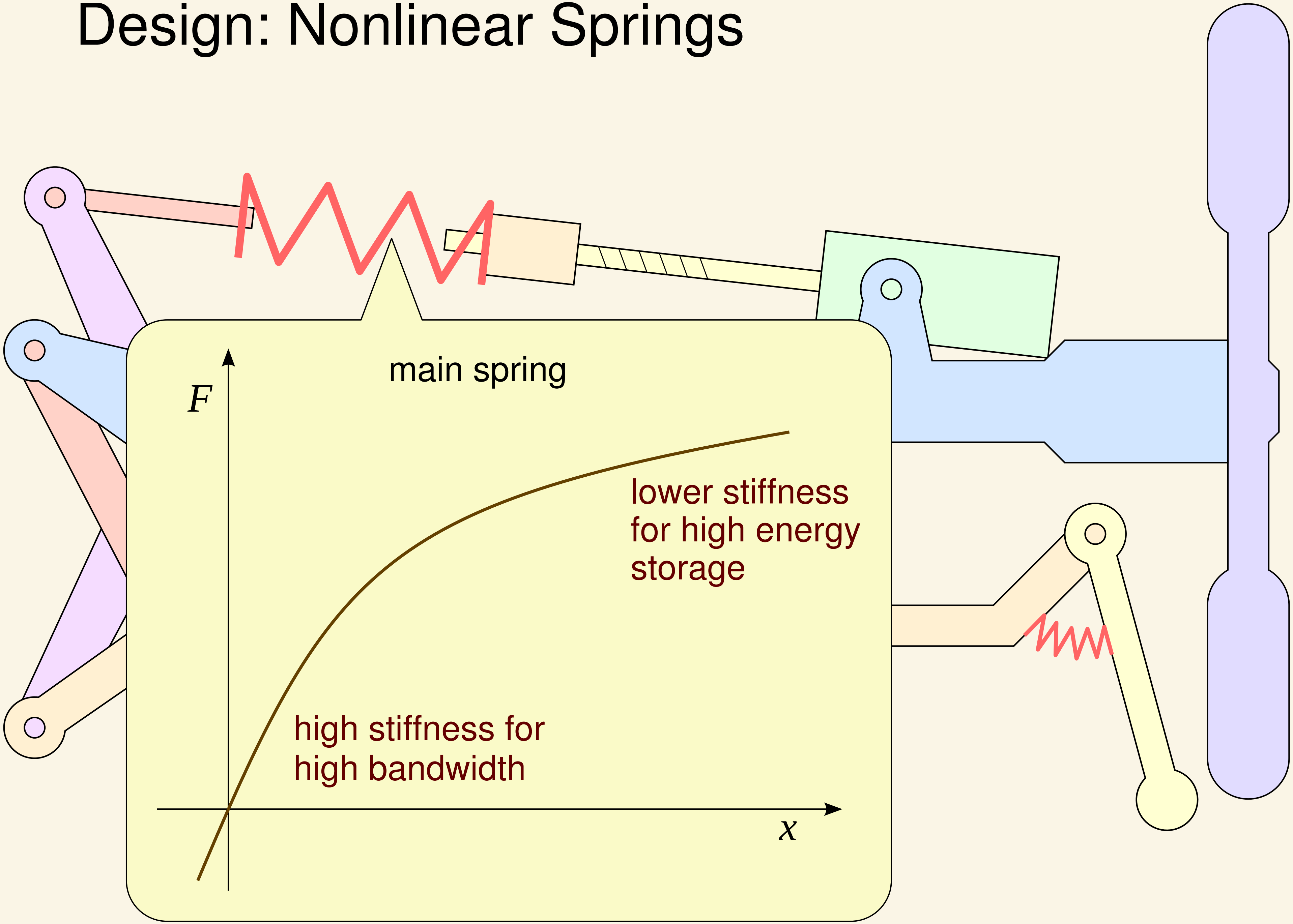
Design: Springy Ankle

During the thrust phase, the ankle *remains flexed*, and the ground reaction forces exert a *positive* moment about the CoM.

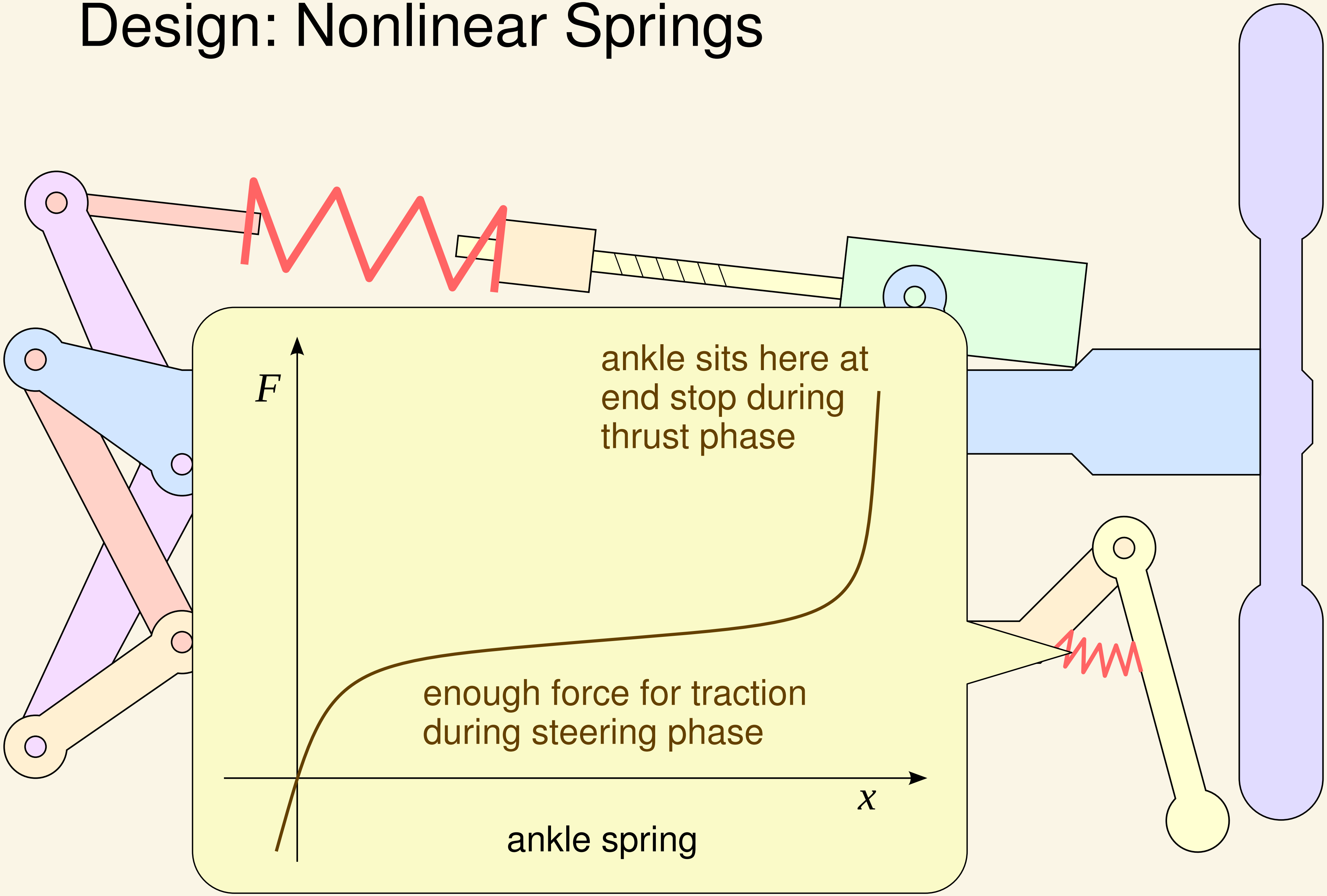
During the steering phase, the ankle *extends*, and the ground reaction forces exert a *negative* moment about the CoM.



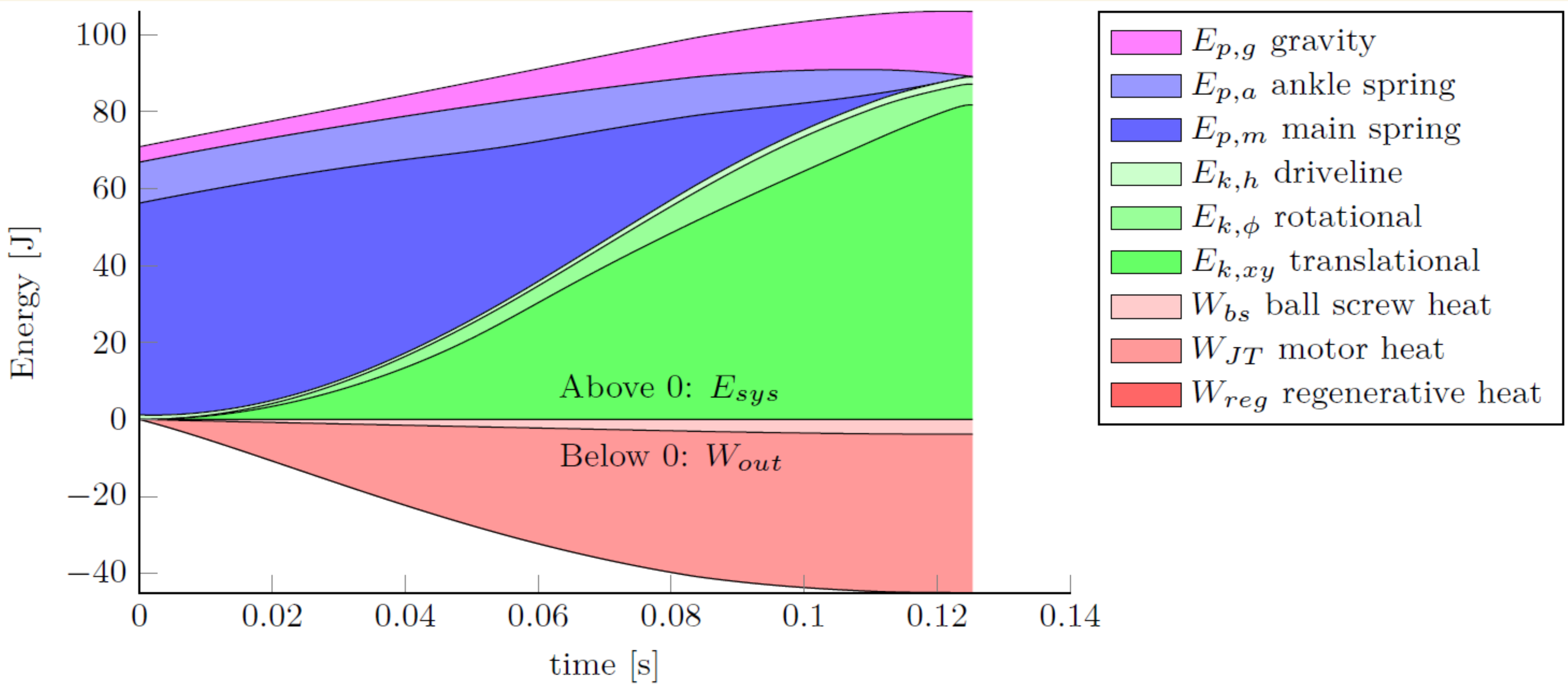
Design: Nonlinear Springs



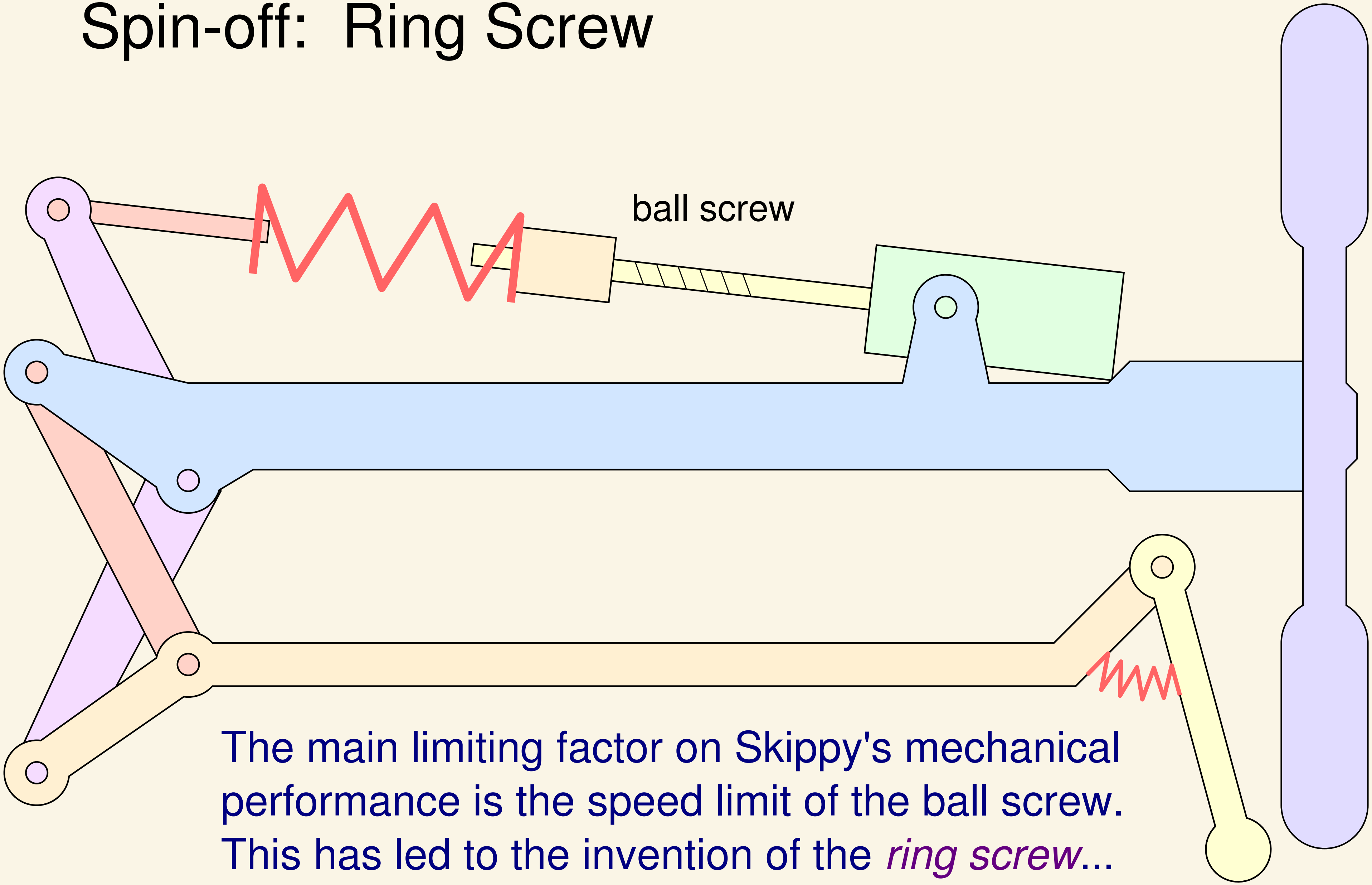
Design: Nonlinear Springs



Design: Energy Flows

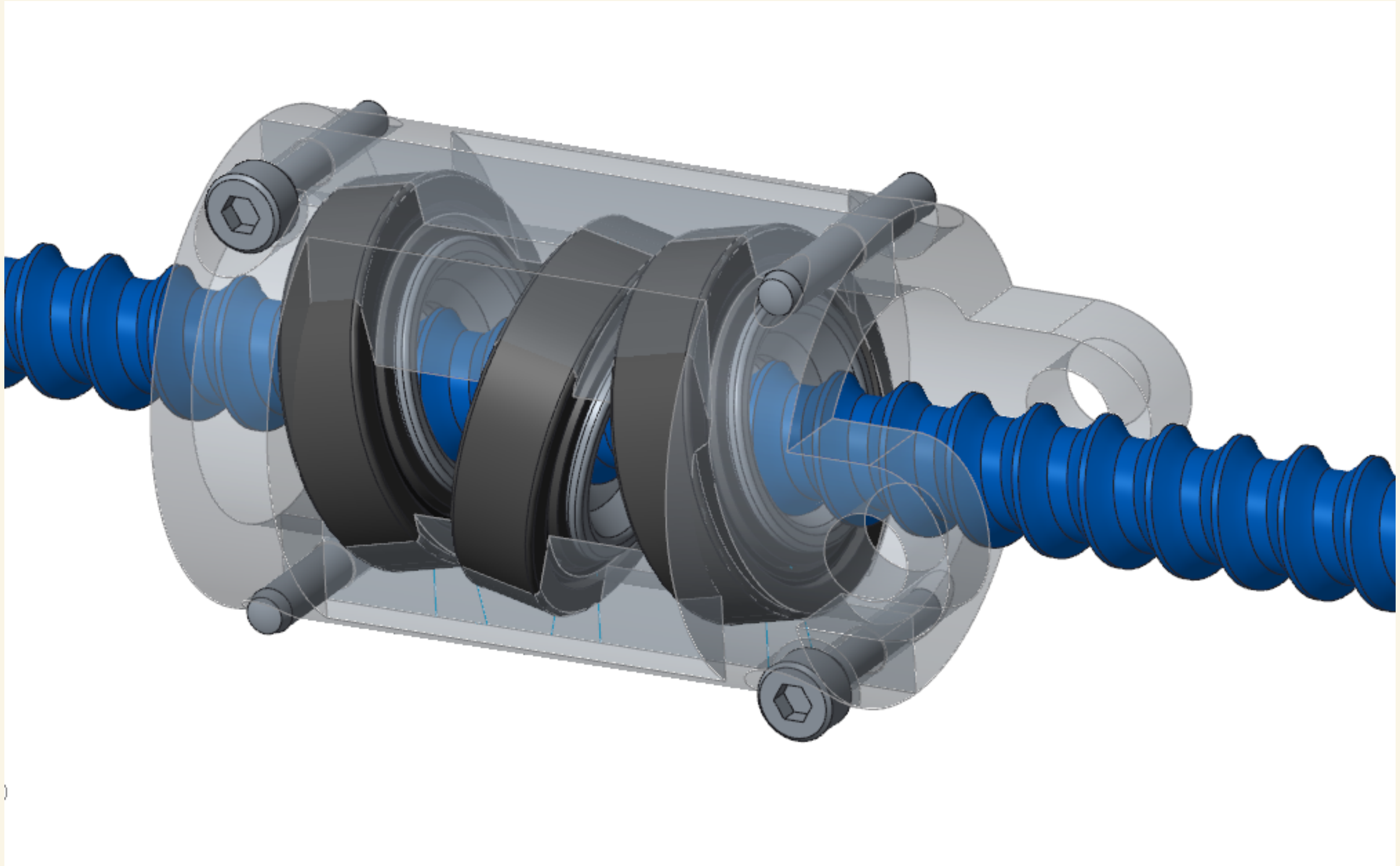


Spin-off: Ring Screw



The main limiting factor on Skippy's mechanical performance is the speed limit of the ball screw. This has led to the invention of the *ring screw*...

Spin-off: Ring Screw



Three rings mounted in bearings make theoretically perfect rolling contact with the screw rod. This mechanism performs the same function as a ball screw, but without the speed limit.

Results

Can Skippy really do everything with only two actuators? We have been working on this question, and now have several results.

Hopping:

- small single hops in 2D with a target landing point, beginning and ending in a balanced position, using only one actuator
  - controlled crouch and forward lean
  - controlled launch achieving accurately a desired dynamic state at lift-off
  - in-flight control of foot motion, and accurate foot placement on landing
  - recovery of balance after landing

Results

Balancing:

- quantitative measures of a robot's physical ability to balance
  - *guides and evaluates the design*
- a new model of the physical process of balancing
  - *leads to new and better control systems*
- high-performance balancing in 2D
  - *balance any planar mechanism, even with kinematic loops*
  - *use any combination of joint motions for balancing*
  - *perform large, fast movements without falling over*
  - *fast, accurate tracking by leaning in anticipation*
- bend-swivel balance control in 3D

Acknowledgments:

energy flow graph	—	Sep Driessen
ring screw drawing	—	Gianluca Pane
hopping video	—	Morteza Azad

For more information: http://royfeatherstone.org/skippy/

THE END