Microgravity Environment Interpretation Tutorial

NASA Glenn Research Center

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Acronyms and Abbreviations

a – acceleration, (or Stokes' radius)
F – force
m - mass
A – area
μ – viscosity
g - unit gravity (9.8 m/sec^2)
χ- diamagnetic susceptibility
B – magnetic field
M – magnetic moment
ω- angular frequency
t – time
τ – period of rotation
r - radius

<x> - root mean square distance
D – diffusion coefficient
V_{sed} – sedimentation velocity
V- volume
N_o/N_R – particle concentration ratio (center:perimeter)
RPM – Rotations per Minute
ρ - density
ω - angular frequency
N_h/N_0 – particle concentration ratio (top:bottom)
y – linear distance
K_b – Boltzman's constant
R – radius (of container)
T – temperature

Simulated vs. Real 0g

- An object infinitely far from any other mass, at rest or in motion and neglecting gravity generated by itself, experiences true 0-g
- **Freefall** (linear, orbital or parabolic) results in weightlessness via induced 'accelerated motion' vs. **Terminal Velocity**
- Clinostat time averages the g-vector and prevents unidirectional sedimentation
- Neutral Buoyancy, Tail Suspension and Diamagnetic Levitation partially offset various effects of gravity

Simulated vs. Real 1-g

- Gravity arises due to attractive force of a mass
- Acceleration (linear or centripetal)
- **Point source vs. body force**
- Diamagnetic levitation can be used to impart a body force similar to gravity

Simulating (aspects of) Weightlessness on Earth

- Drop Tower
- Parabolic Flight

- Bed Rest
- Water (Dry) Immersion
- Neutral Buoyancy

- Tail Suspension
- Nerve Crush
- Immobilization

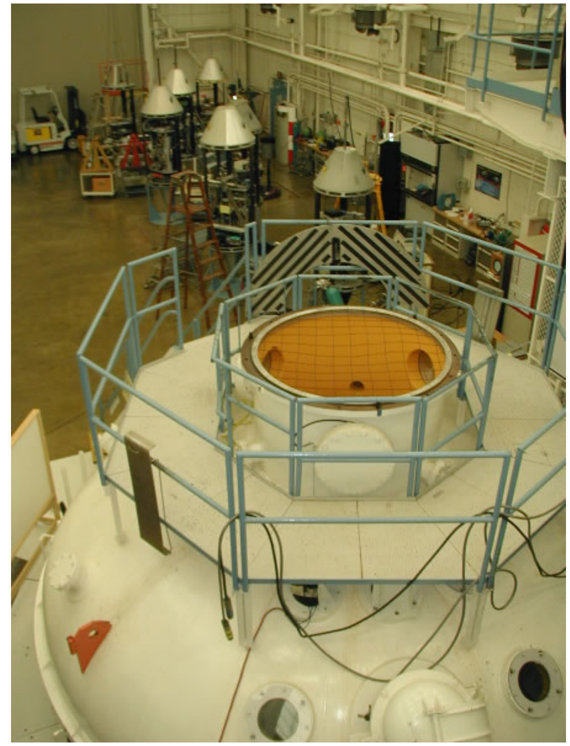
- Clinorotation
- Free Fall Machine (bouncing)
- Diamagnetism
- High viscosity / low density delta

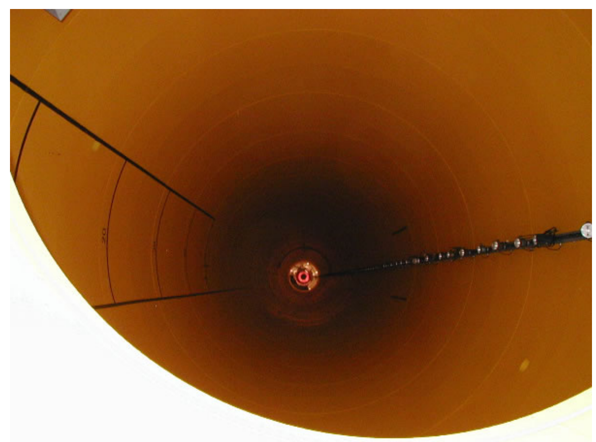
see also: GROUND-BASED MODELS FOR STUDYING ADAPTATION TO ALTERED GRAVITY, Emily R. Morey-Holton, Ph.D., NASA Ames Research Center, Moffett Field, CA (http://spacebio.net/Sptopics/gm_resource/reed/ground_models.doc)

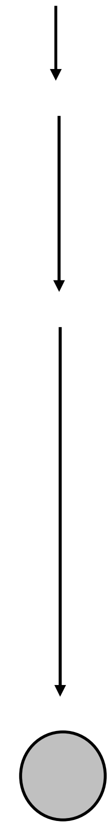

Zero Gravity Facility

Drop Tower

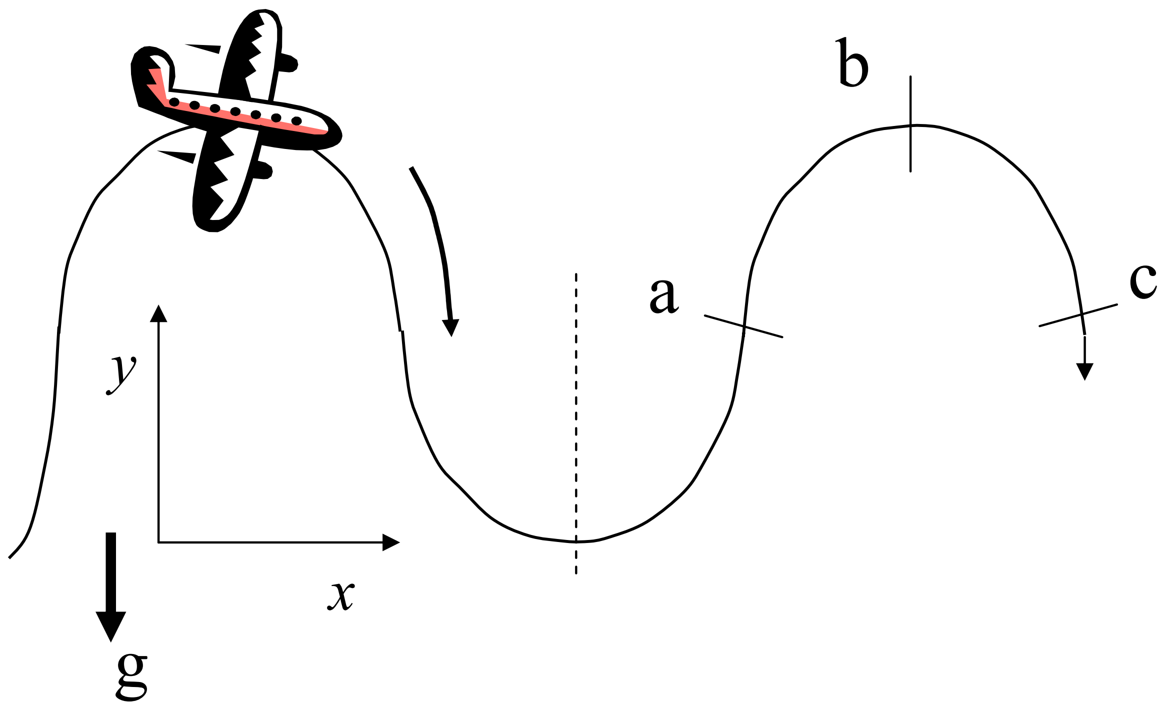
NASA Glenn Research Center
Space Experiments Laboratory



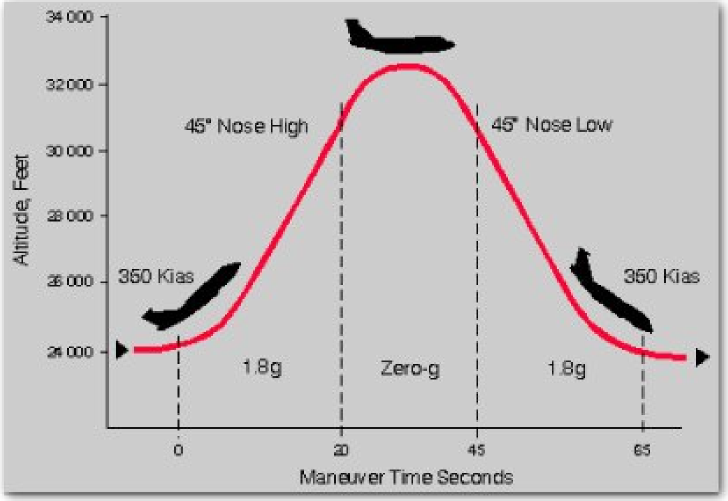




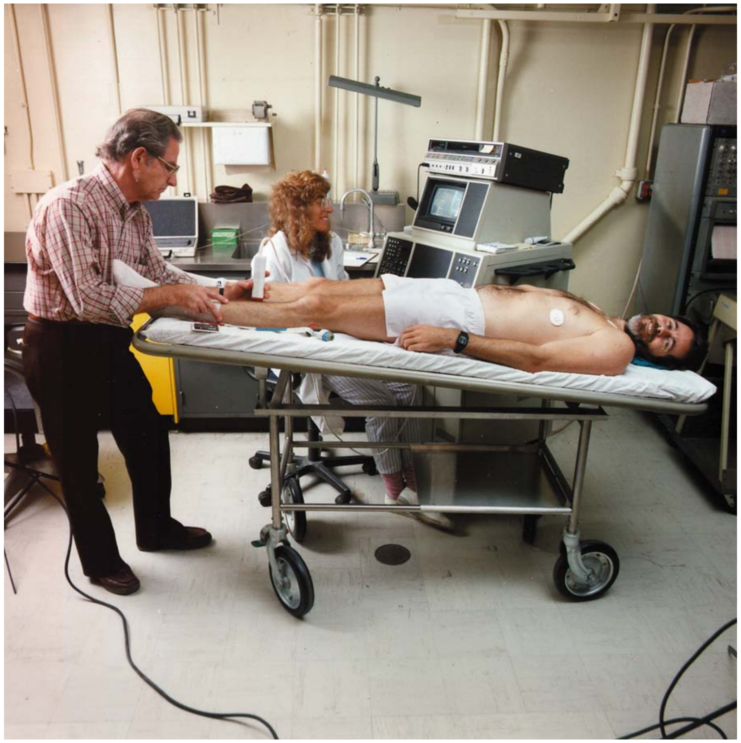
Parabolic Flight

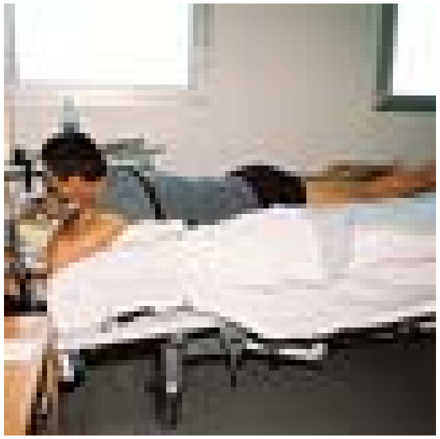


When is weightlessness experienced?


34 000
32 000
30 000
28 000
26 000
24 000
Altitude, Feet
45° Nose High
45° Nose Low
350 Kias
350 Kias
1.8g
Zero-g
1.8g
0
20
45
65
Maneuver Time Seconds

Bed Rest (6-degree head down tilt)





http://spacebio.net/Sptopics/gm_resource/Head_Down_Tilt.jpeg

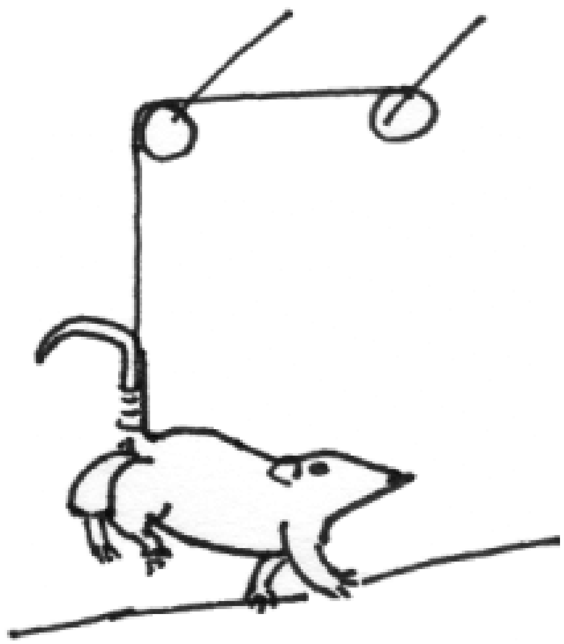
Dry Immersion

Neutral Buoyancy

http://www.jsc.nasa.gov/dx/dx12/htmls/photos.htm

Rodent Models

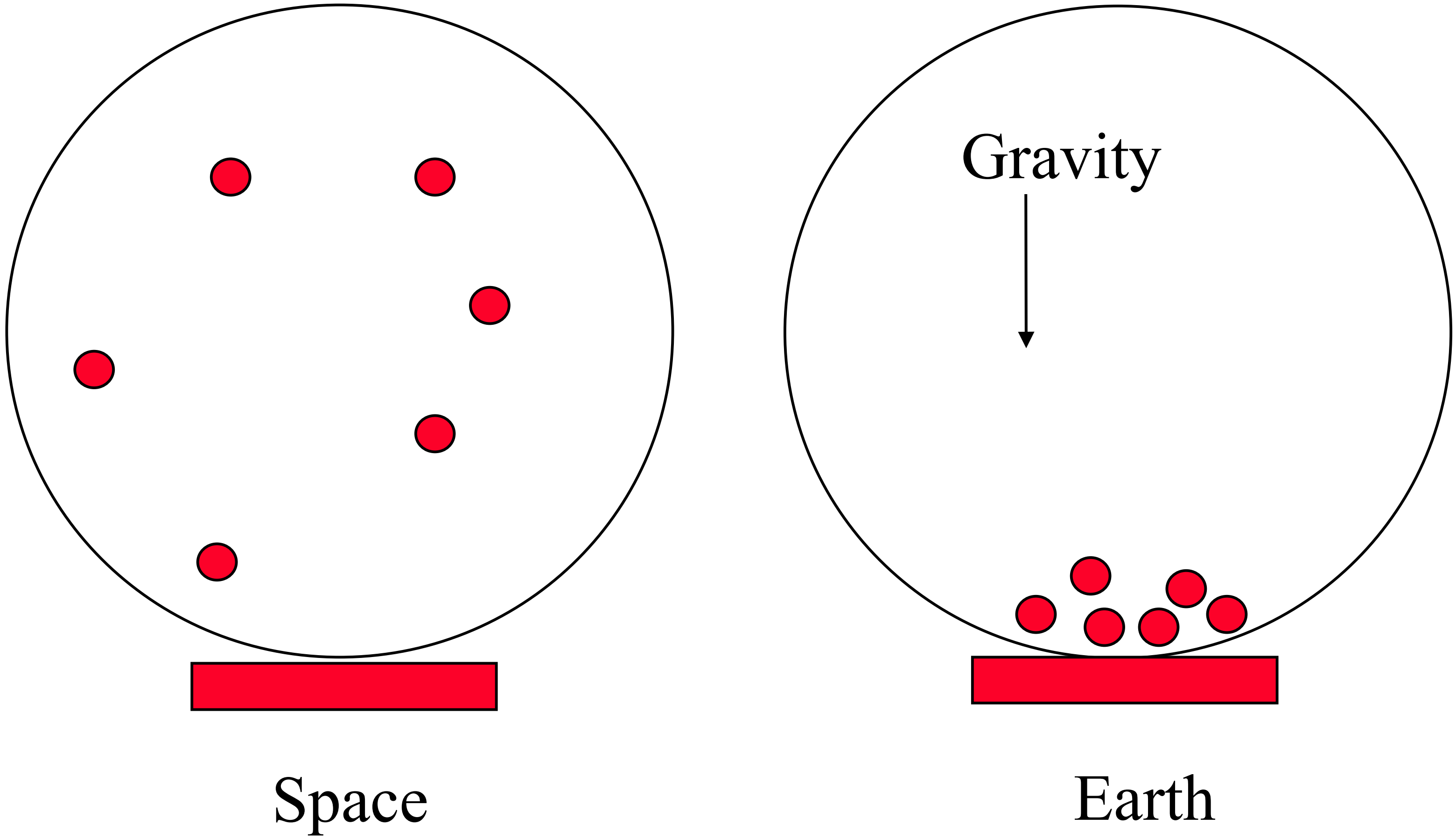
- Tail Suspension
- Nerve Crush
- Immobilization

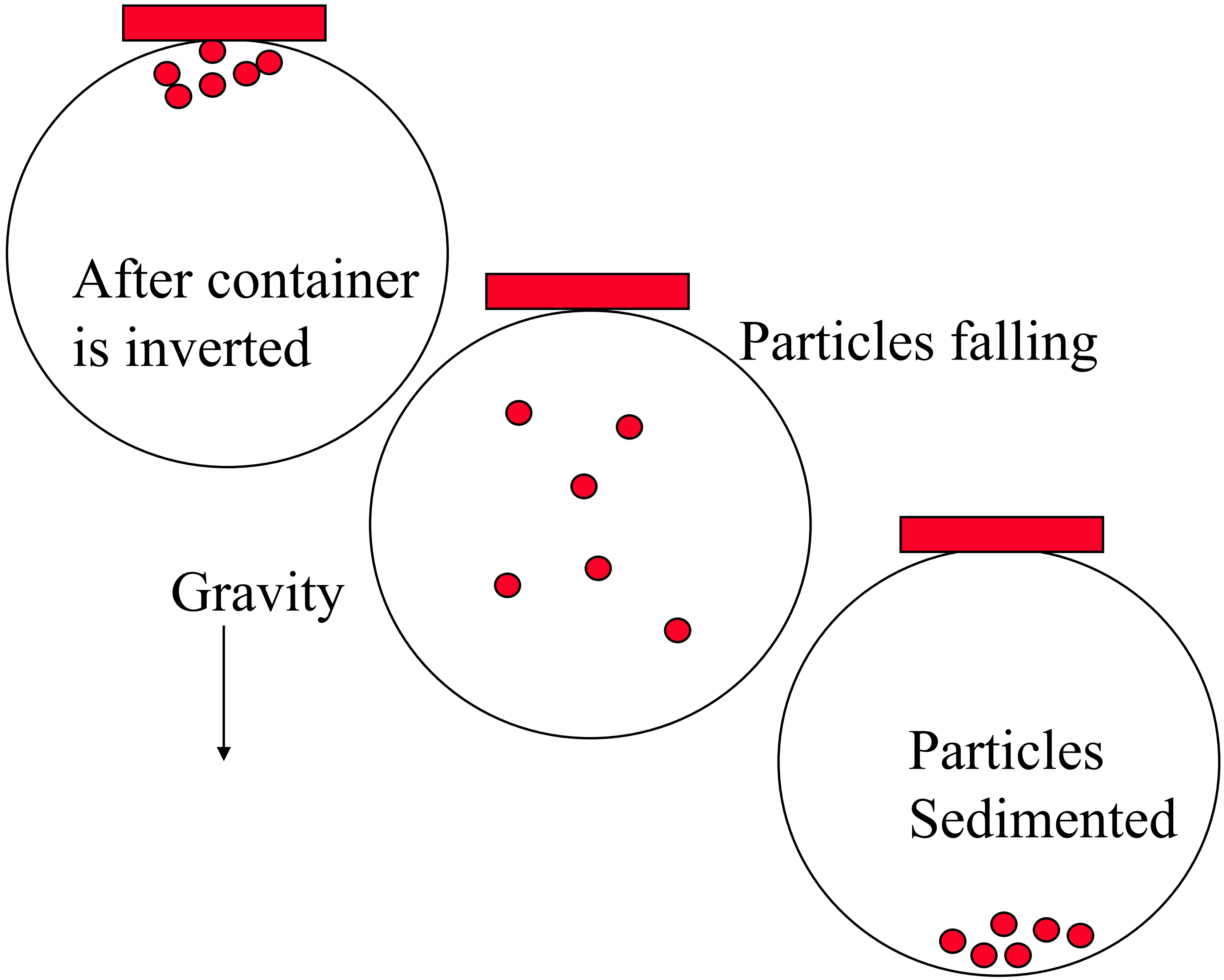


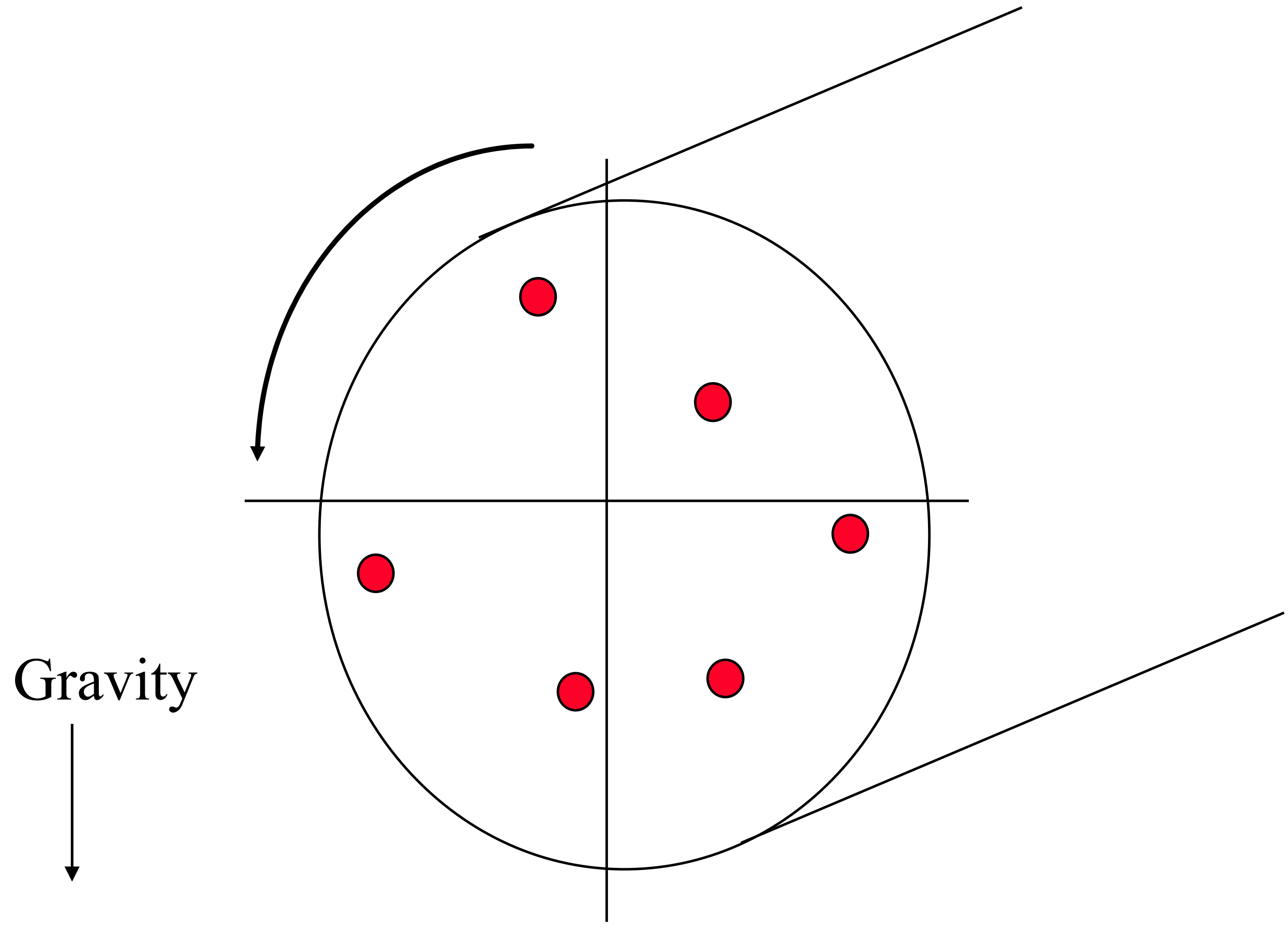
Clinorotation

Klaus, D.M., Todd, P. and Schatz, A. (1998): Functional Weightlessness During Clinorotation of Cell Suspensions". *Advances in Space Research* **21 (8/9)**: 1315-1318

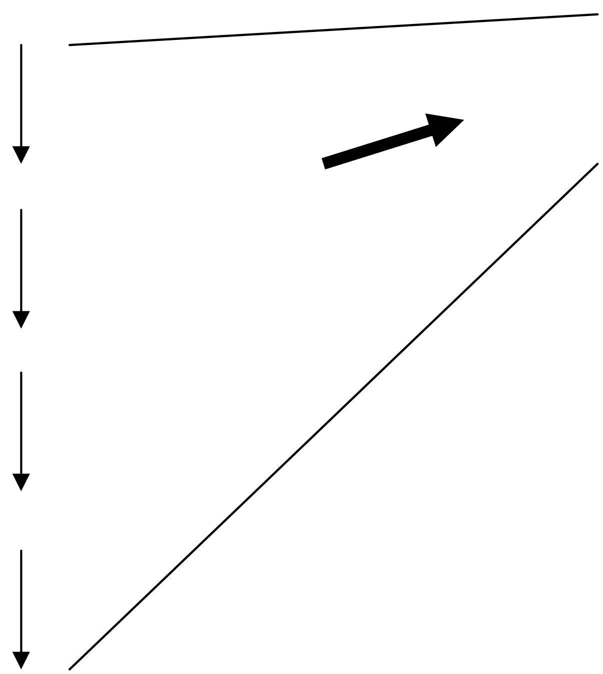
Simulating Partial-g on Earth and 1-g in Space




After container is inverted
Particles falling
Gravity
Particles Sedimented

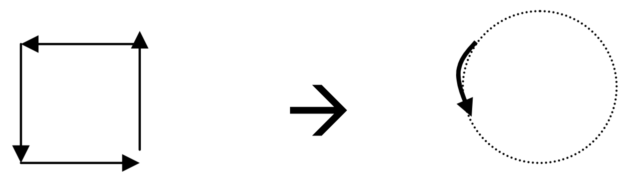

Gravity

Terminal Velocity in a Viscous Medium



$\Sigma F = ma = drag$
and velocity = Constant

Terminal Velocity in a Rotating Viscous Medium



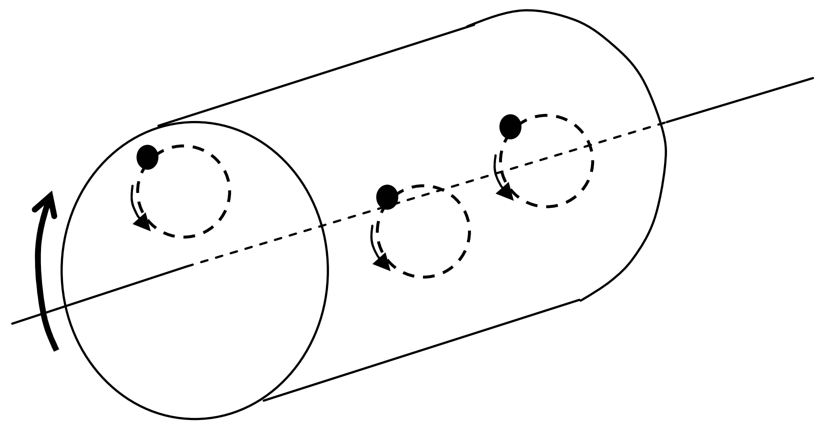
Faster rotation

→Smaller circumference
< Brownian motion ?
decreased sensor response time
but increased centrifugation

Slower rotation

→Larger circumference
(more movement)
increase sensor response time
but less centrifugation

Simplified Description



(1-D) Clinostat

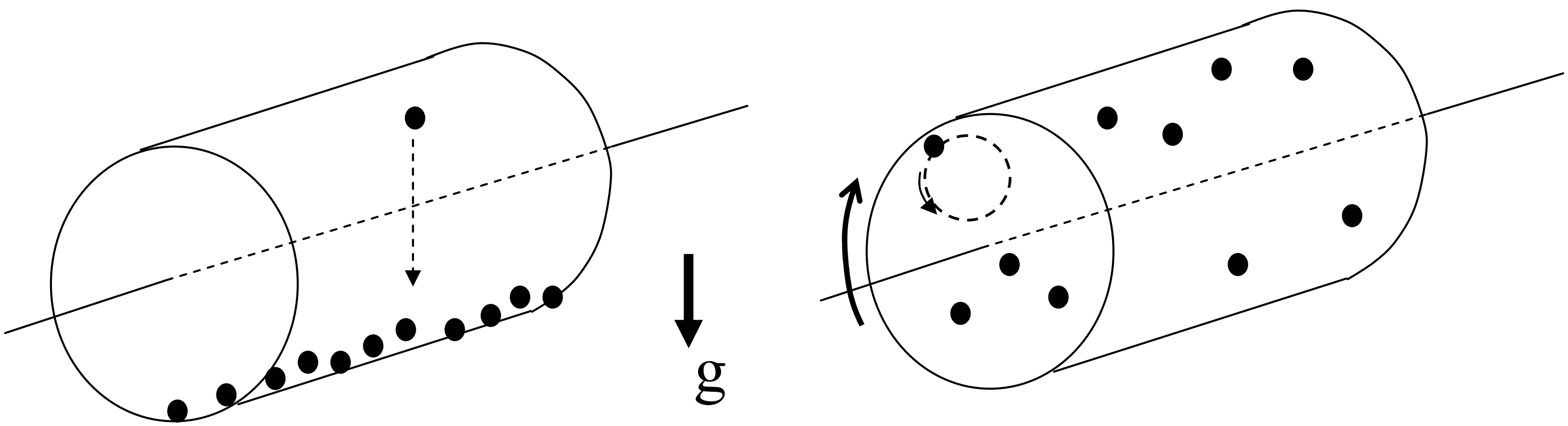
Incline (rotate) — Static

Signal Response Time — Extracellular Mass Transfer

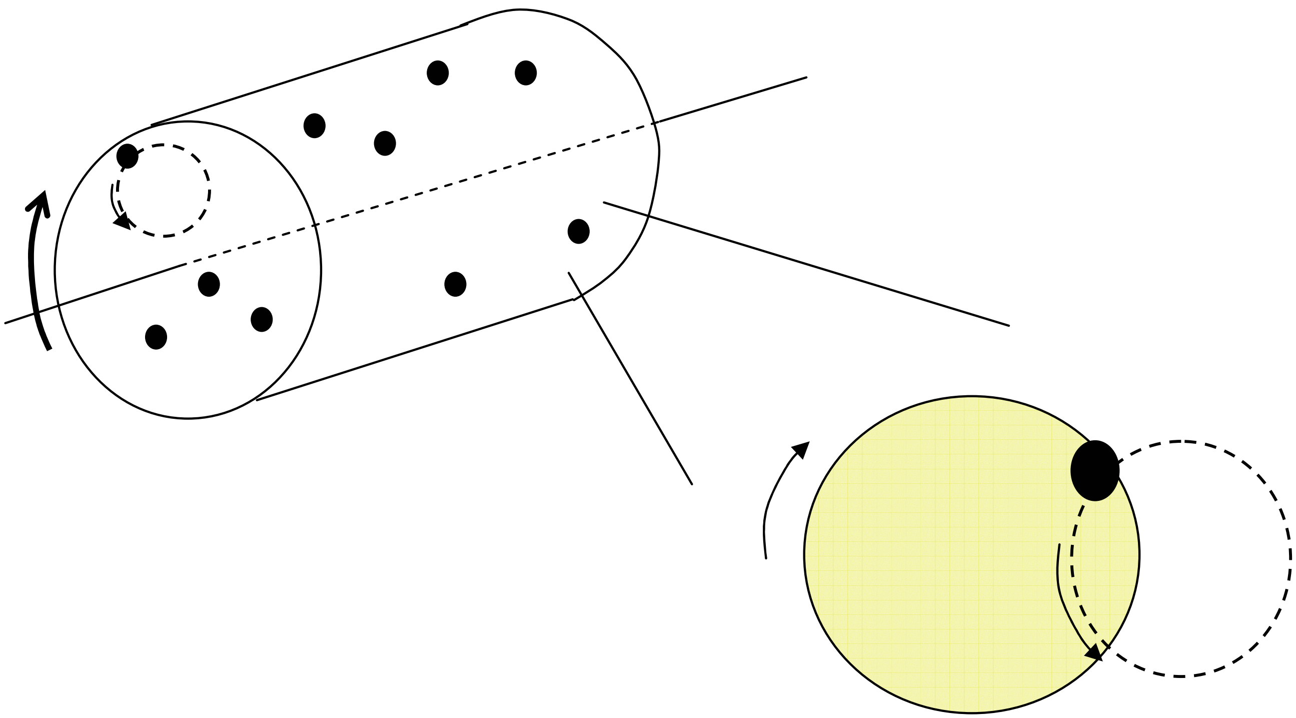
Basic Premise of the Clinostat for Suspension Cultures

1-g Stationary

Clinorotation

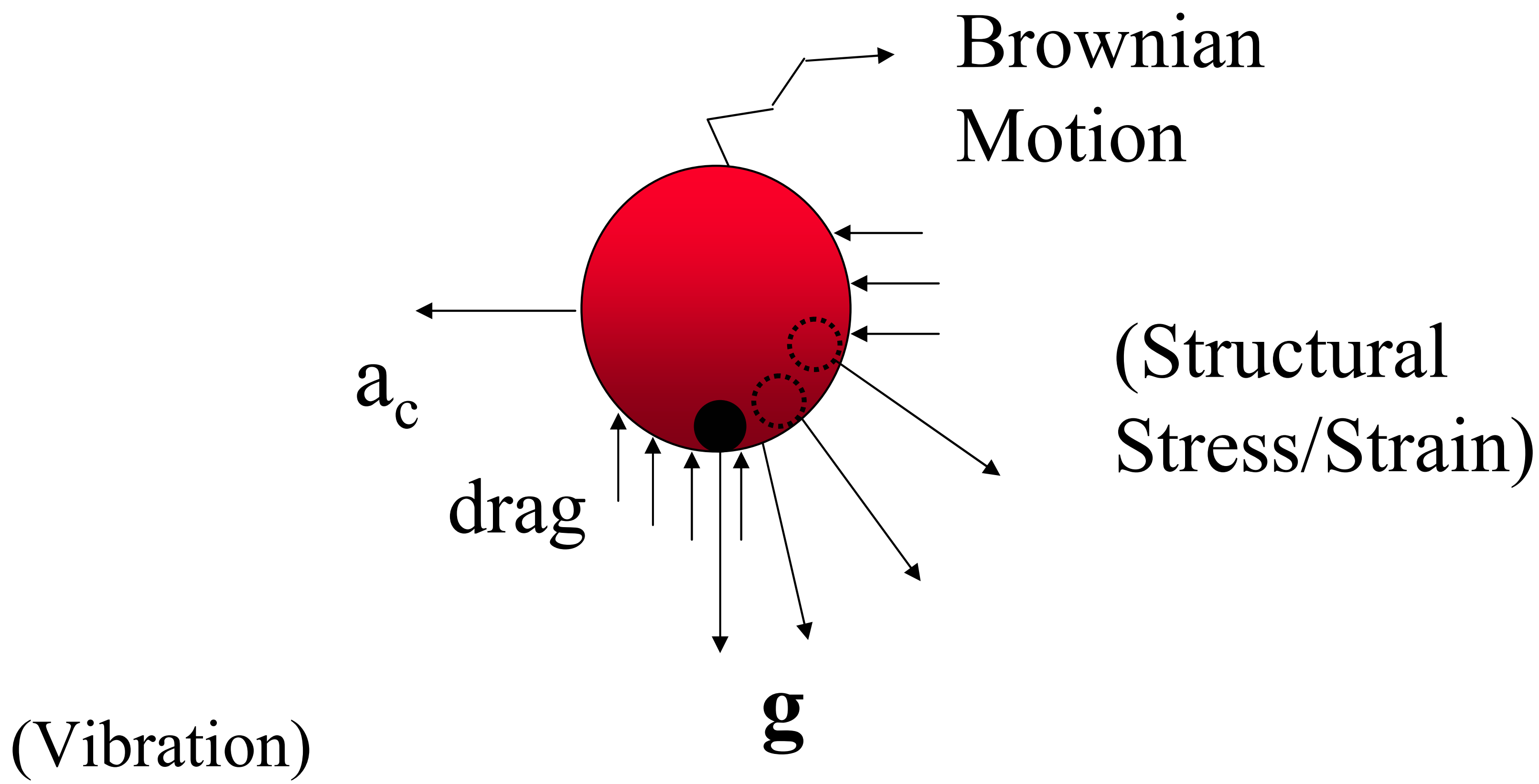


g-vector is time-averaged to zero as a function of rotation rate & cumulative sedimentation is prevented



Potential for counter-rotating components
Cells, byproducts (& organelles?)

Primary Forces Acting on a Suspended Cell in a Clinostat



Forces within a Clinostat can be balanced to achieve "Functional Weightlessness"

$<x>^2 = 2Dt$

$V_{sed} = 2/9\ (\rho_{particle} - \rho_{fluid})\ (g/\mu)\ a^2$

$y = V_{sed}\ t$

$t = 2\pi\ r / V_{sed}$

$RPM_{min} = f$ (response time, t)

$\omega = 2\ \pi\ (1/\tau)$

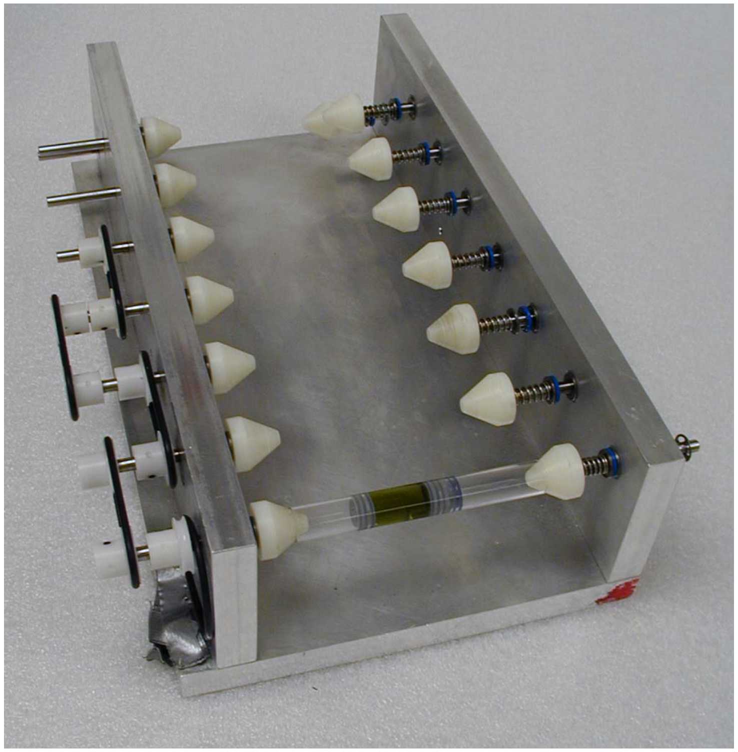
$a_c = R\ \omega^2$

$n_0 / n_R = e^{-\{V(\Delta\rho)a_c R / k_b T\}}$

$RPM_{max} = f$ (equilibrium distribution and experiment duration)

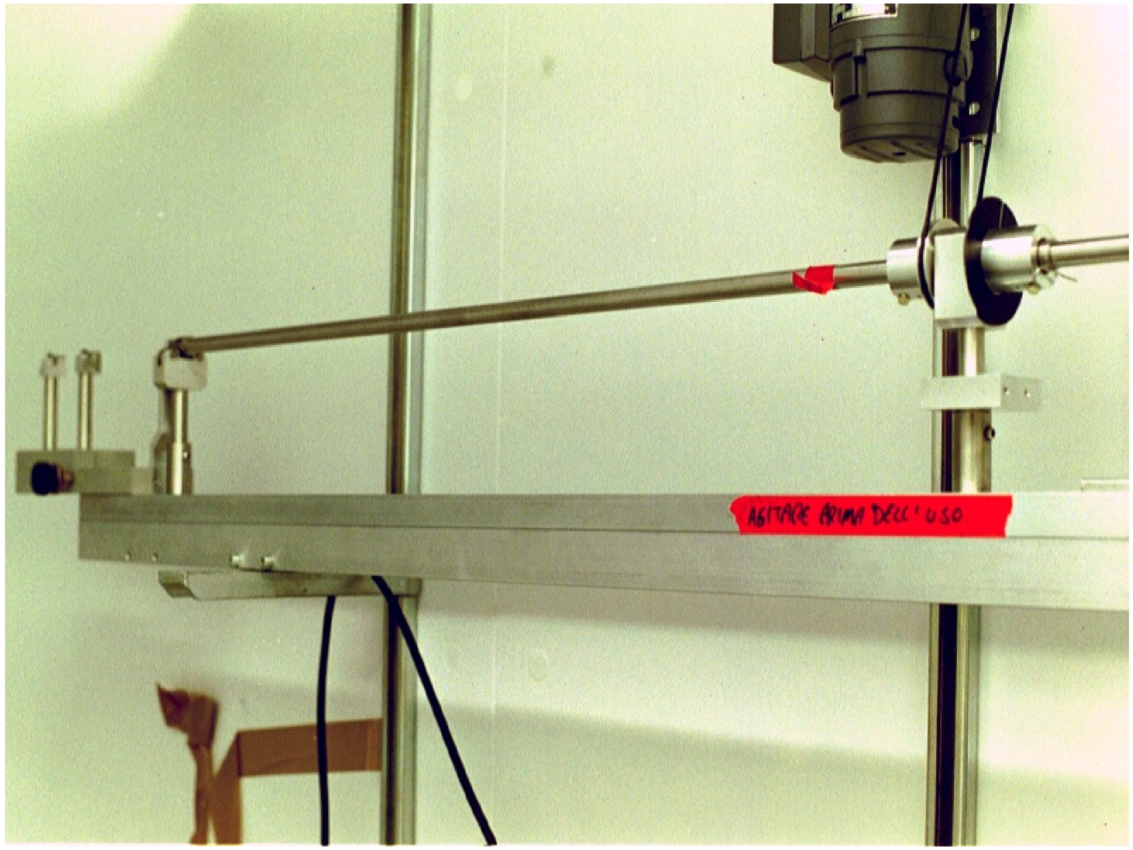
Klaus, D.M., Todd, P. and Schatz, A. (1998): Functional Weightlessness During Clinorotation of Cell Suspensions". *Advances in Space Research* **21 (8/9)**: 1315-1318

1-D Clinostat

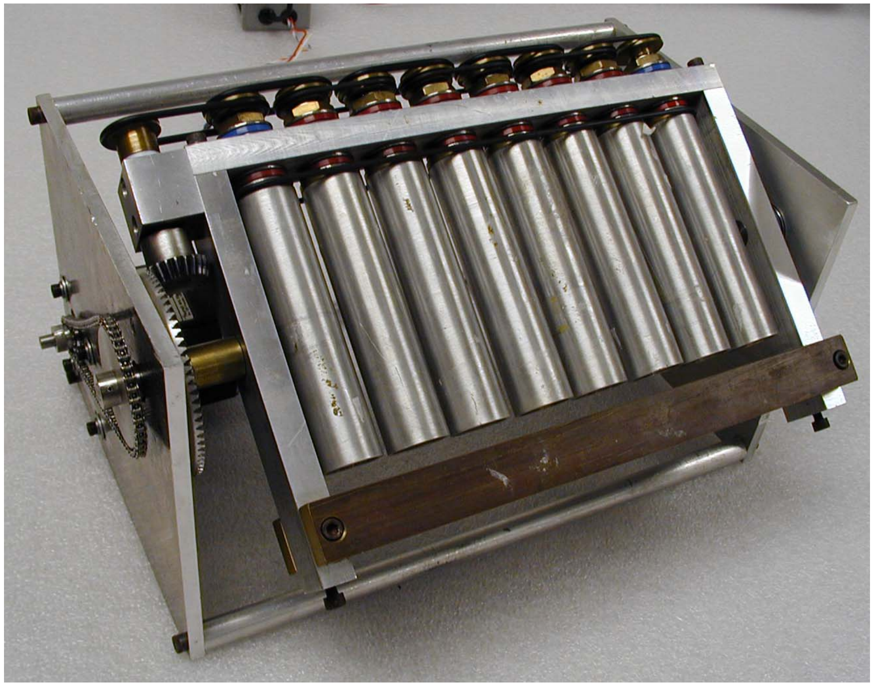


BioServe Space Technologies

Fast Rotating Clinostat



2-D Clinostat



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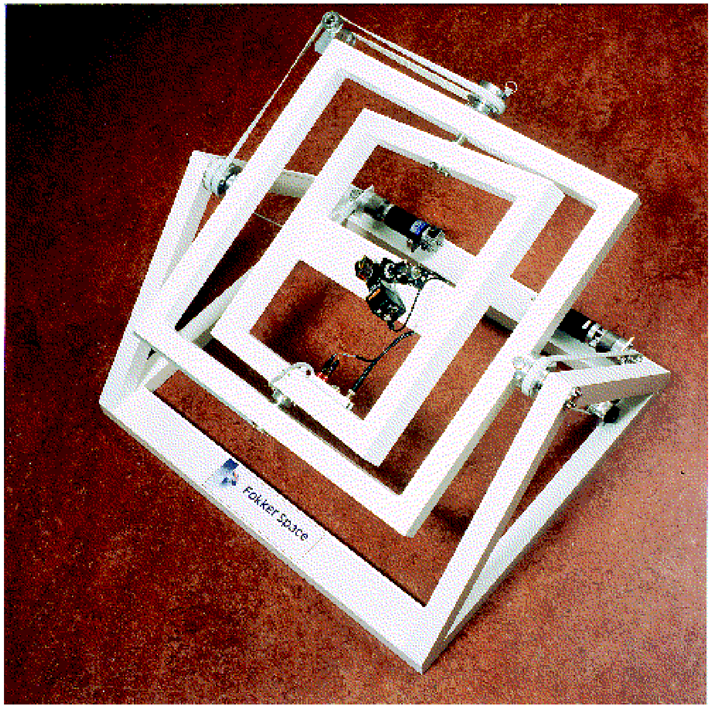
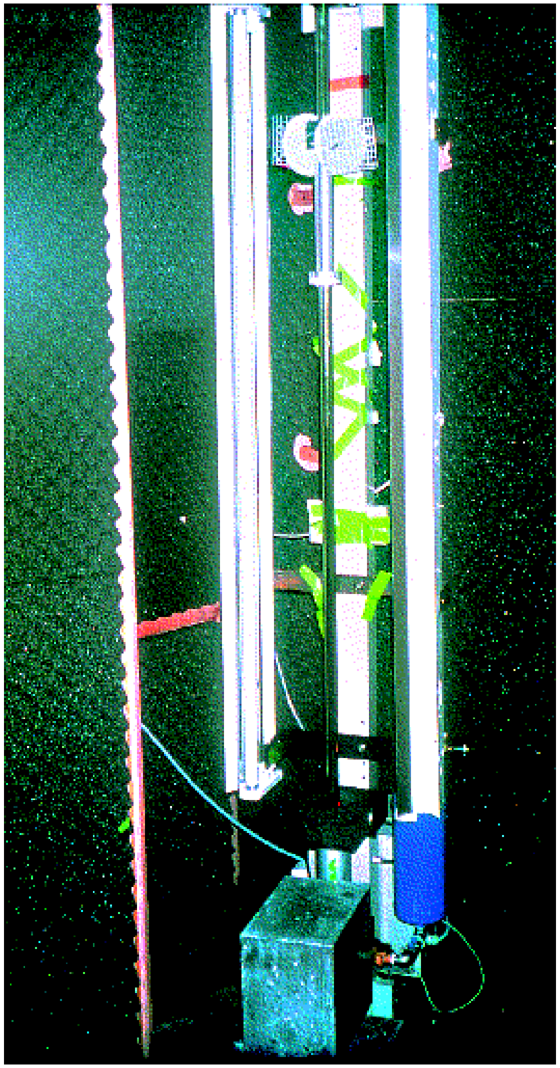
3-D Clinostat



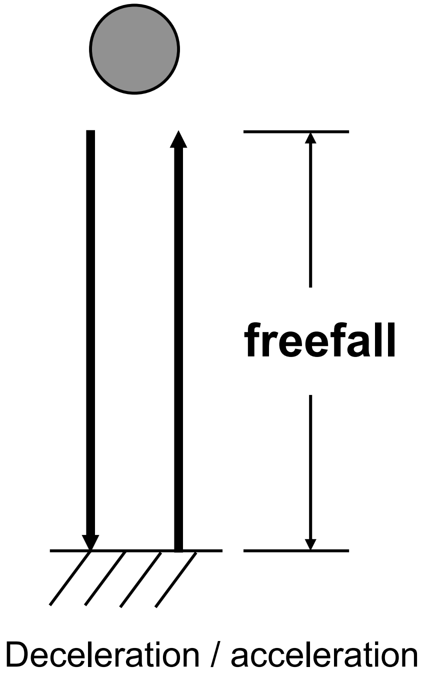
'Random Positioning Machine'
Fokker Space and Systems
Leiden, the Netherlands

http://esapub.esrin.esa.it/micrgra/micrv9n1/mesv9n1.htm



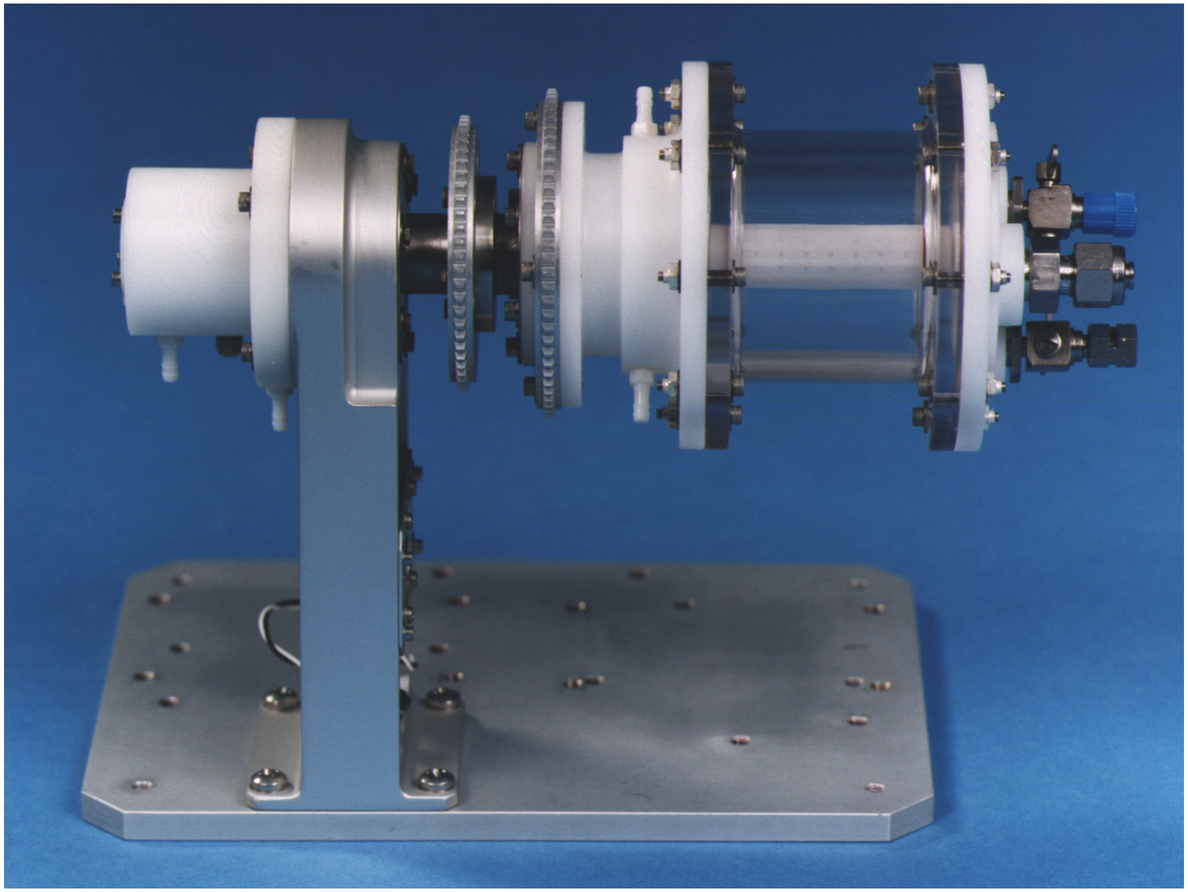
Free Fall Machine

(located at the BioCentrum of the University of Amsterdam)



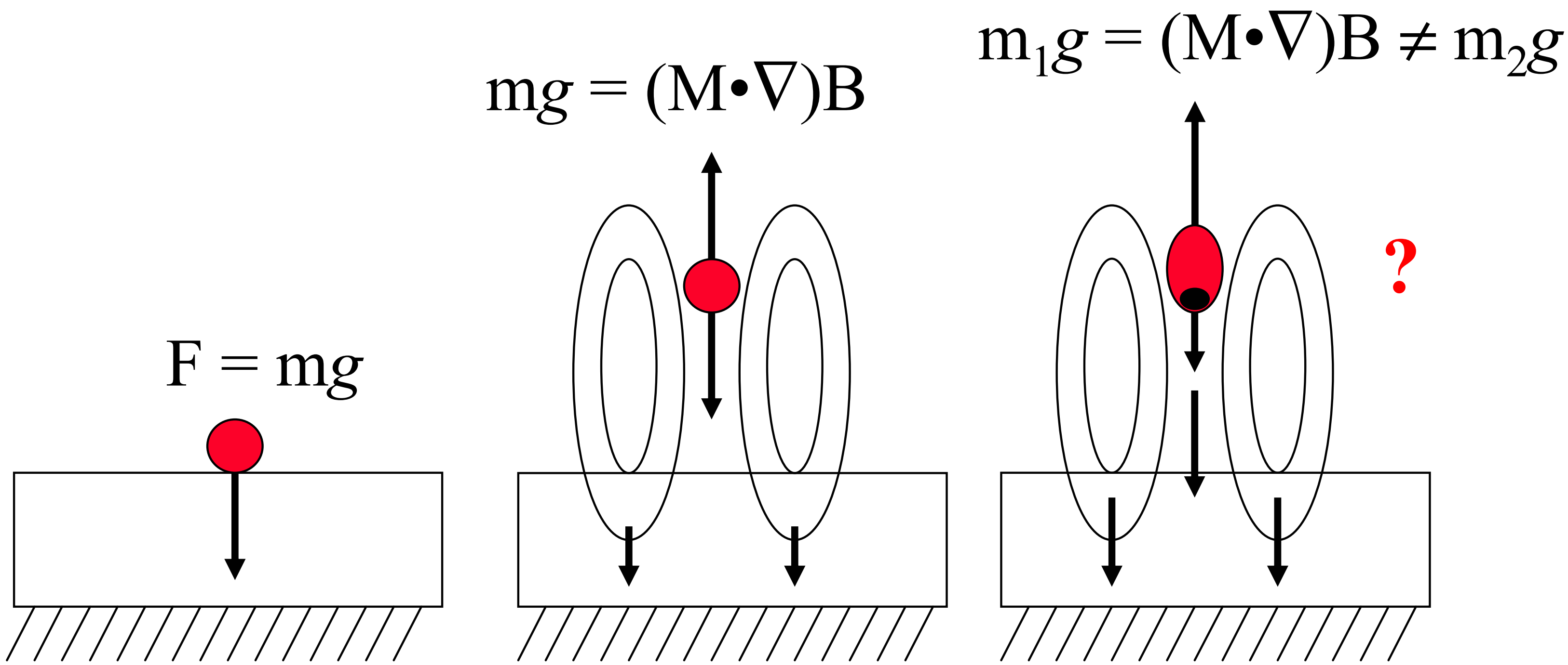
http://esapub.esrin.esa.it/microgra/micrv9n1/mesv9n1.htm

Rotating Wall Vessel (RWV) Bioreactor



http://science.msfc.nasa.gov/newhome/br/bioreactor.htm

Diamagnetic Levitation Force due to Magnetic Susceptibility χ



- Most biomaterials have a diamagnetic ratio of $\chi / \rho \approx 10^{-5}$ cm^3/g
- Water, tissue, bones and blood only differ by several percent
- Implies that gravity can be uniformly compensated within 0.1 *g*
- Stability?

Geim,A. (1998) *Physics Today* 51:9 36-39

Proposed ground control summary matrix

Primary variable isolation of gravity (or inertial acceleration) -dependent / -independent factors

	1*g*		0 *g*	Clino stat	RWV	Che mos tat	Centrifuge				Stir	NB	Embed	Agar	Le vita ted
							Grnd >1g		Flight 1g						
	F*	S					F	S	F	S					
Cell Falling	√	X	X	√	√	√	√	X	√	X	√	X	X	X	X
Cell Brownian motion	√	X	√	√	√	√	√	X	√	X	√	√	√	X	√
Cell (free) motility	√	?	√	√	√	√	√	?	√	?	√	√	X	X	√
Accumulation on bottom	X	√	X	X	X	X	X	√	X	√	X	X	X	√	X
Cell weight	√	√	X	√	√	√	√	√	√	√	√	√	√	√	?
Coriolis effect	X	X	X	√	√	X	√	√	√	√	X	X	X	X	X
Inertial shear	X	X	X	X	X	X	√	√	√	√	X	X	X	X	X
Launch forces	X	X	√	X	X	X	X	X	√	√	X	X	X	X	X
Radiation	X	X	√	X	X	X	X	X	√	√	X	X	X	X	?

√ = present, X = absent

1g, (F) = falling, (S) = sedimented; 0g = freefall; RWV = Rotating Wall Vessel; NB = Neutral Buoyant; Embed = embedded in matrix; levitated = diamagnetic levitation

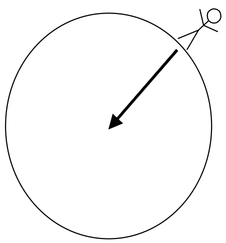
Proposed relative comparison of secondary factors to a 1g (falling) baseline

	1g		0 *g*	Clin ostat	RWV	Che mos tat	Cfg				Stir	NB	Embed	Agar	Lev
							Grnd >1g		Flight 1g						
	F*	S					F	S	F	S					
Shear/Mixing due to falling	-	↓	↓	↔	↔	↔	↑	↓	↔	↓	↔	↓	↓	↓	↓
Shear/Mixing due to motility	-	↓	↔	↔	↔	↔	↔	↓	↔	↓	↔	↔	↓	↓	↔
Shear/Mixing due to stirring (or instability)	-	↔	↔	↑	↑	↔	↔	↔	↔	↔	↑	↔	↓	↓	↑
Shear/Mixing due to mech vibration	-	↔	↔	↑	↑	↑	↑	↑	↑	↑	↑	↔	↔	↔	↔
BP accum in local environ.	-	↑	↑	↑	↑	↔	↓	↑	↔	↑	↓	↑	↑	↑	?
Substrate availability	-	↓	↓	↓	↑	↔	↑	↓	↔	↓	↑	↓	↓	↓	?
O_2 availability	-	↓	↓	↓	↑	↔	↑	↓	↔	↓	↑	↓	↓	↓	?

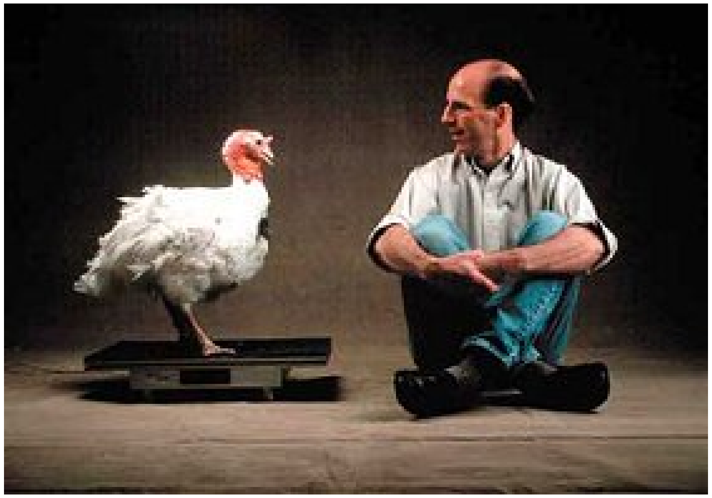
↑ = increased,
↓ = decreased,
↔ = no difference

1g, (F) = falling, (S) = sedimented; 0g = freefall; RWV = Rotating Wall Vessel;
NB = Neutral Buoyant; Embed = embedded in matrix; levitated = diamagnetic levitation

Simulating (aspects of) Weight in Space

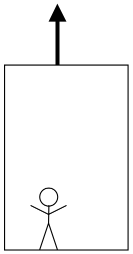


- Linear acceleration
- Centripetal acceleration (Centrifugation)
- Point source loading
- Negative Pressure
- Positive Pressure
- Resistance
- Electrostimulation
- Vibration therapy →
- *Magnetism*

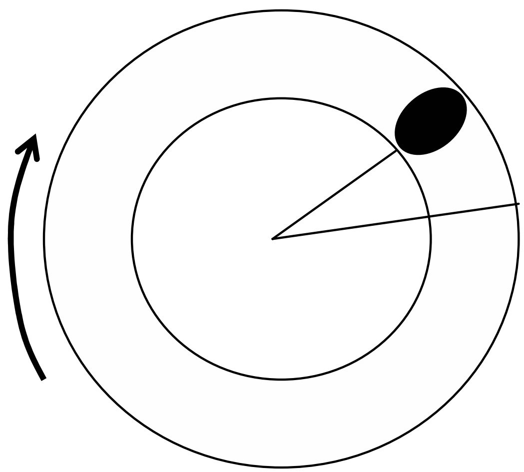


(from http://science.nasa.gov/headlines/y2001/ast02nov_1.htm) Vibration plates such as this one were used for experiments on bone loss involving turkeys, sheep, and rats. Pictured with the turkey is researcher Dr. Clinton Rubin. Photo credit: Cary Wolinsky. This image originally appeared in a National Geographic feature article "Surviving in Space." (see http://www.nationalgeographic.com/ngm/0101/features.html)

Linear Acceleration

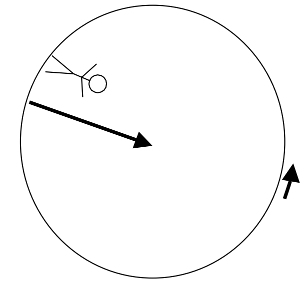


Centrifugation



g-gradient

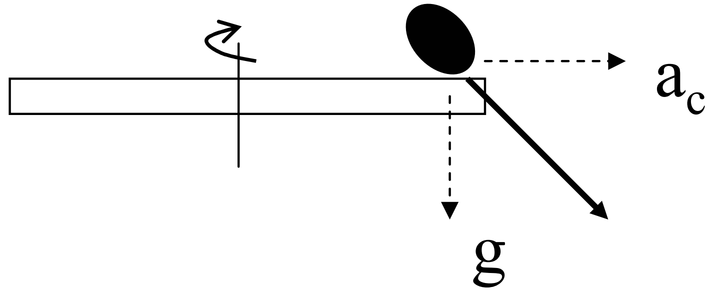
a_c (head) – a_c (toe)



Centripetal Acceleration

$$a_c = r_1 \omega^2$$

$$\omega = 2 \pi / \tau$$

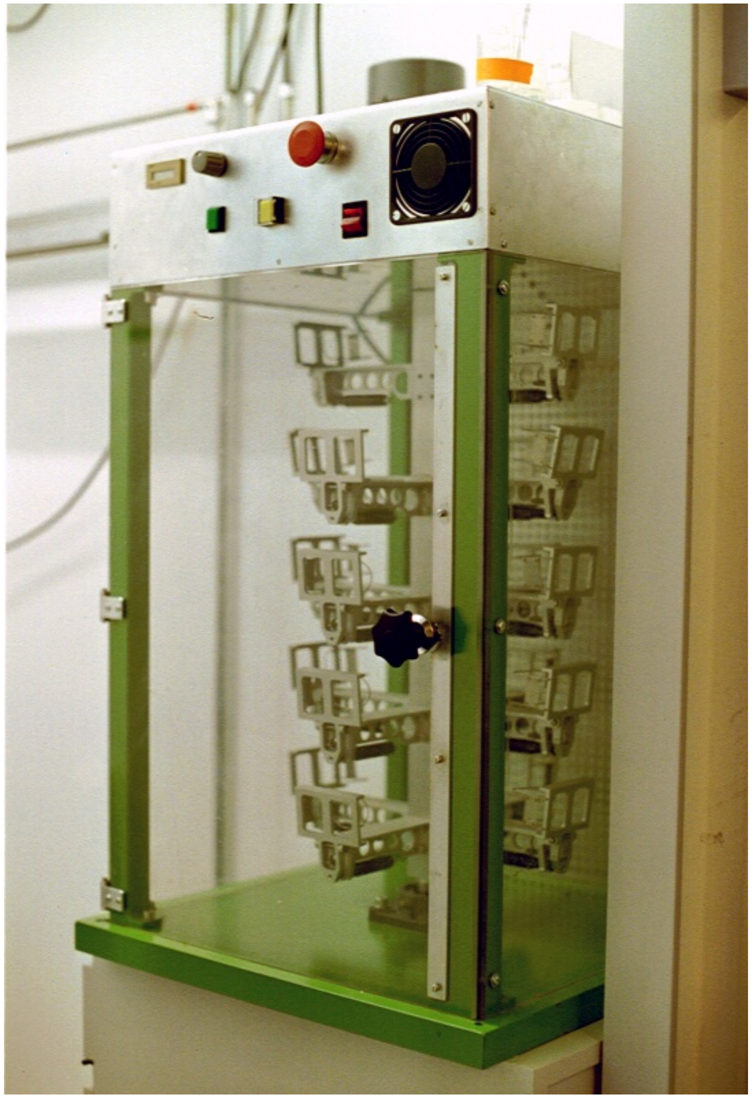


$$a_{net} = \sqrt{a_c + g}$$

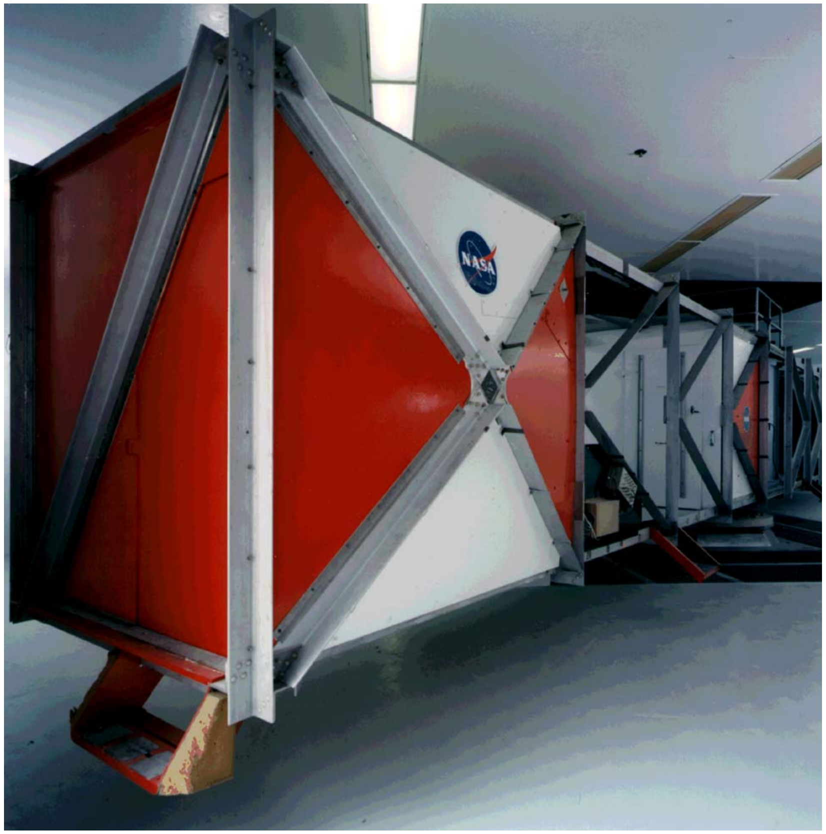
a_c will always be > 1g on Earth

Coriolis effect
Cross coupled angular acceleration

Hyperfuge

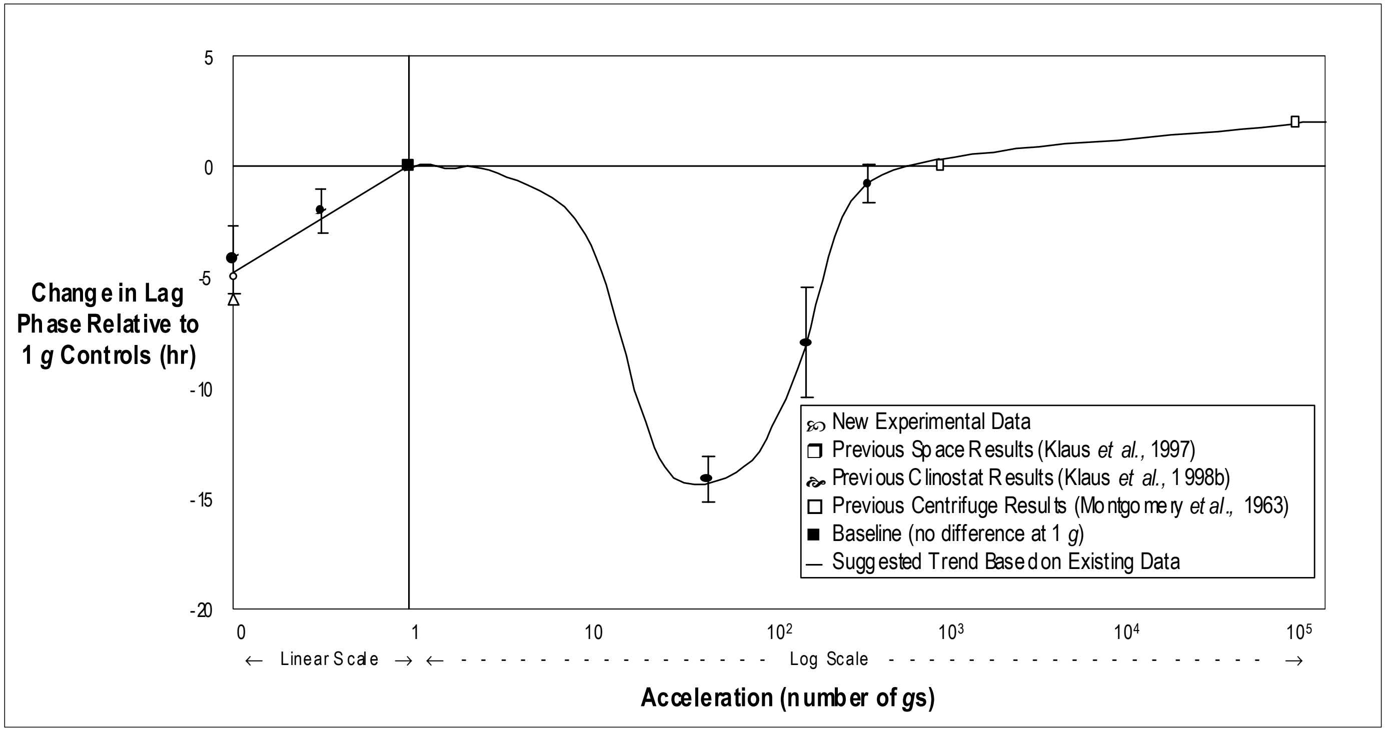


Human Research Centrifuge Facility at NASA Ames Research Center

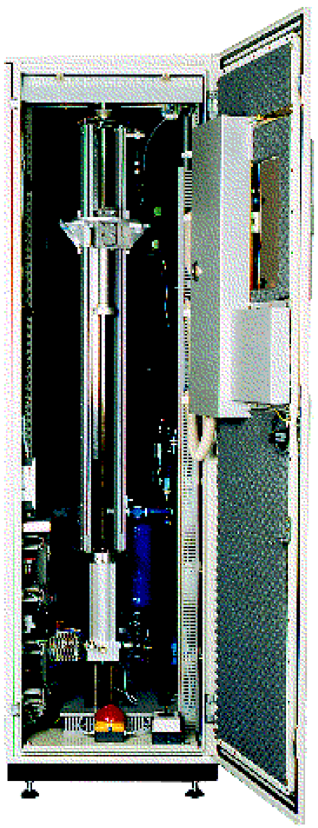


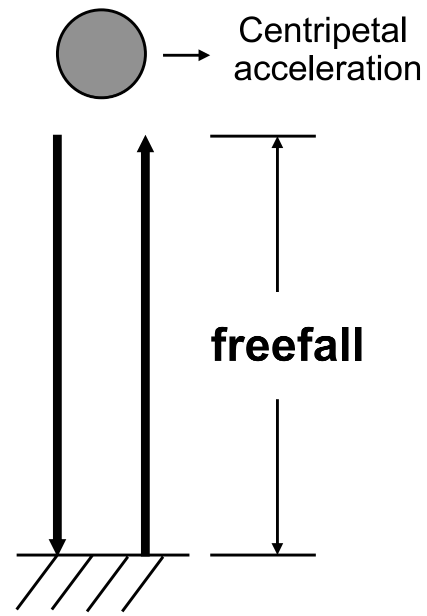
Non-linear Responses

Effect of Acceleration on Lag Phase



plot from Brown. (1999) Doctoral Dissertation, University of Colorado, Boulder

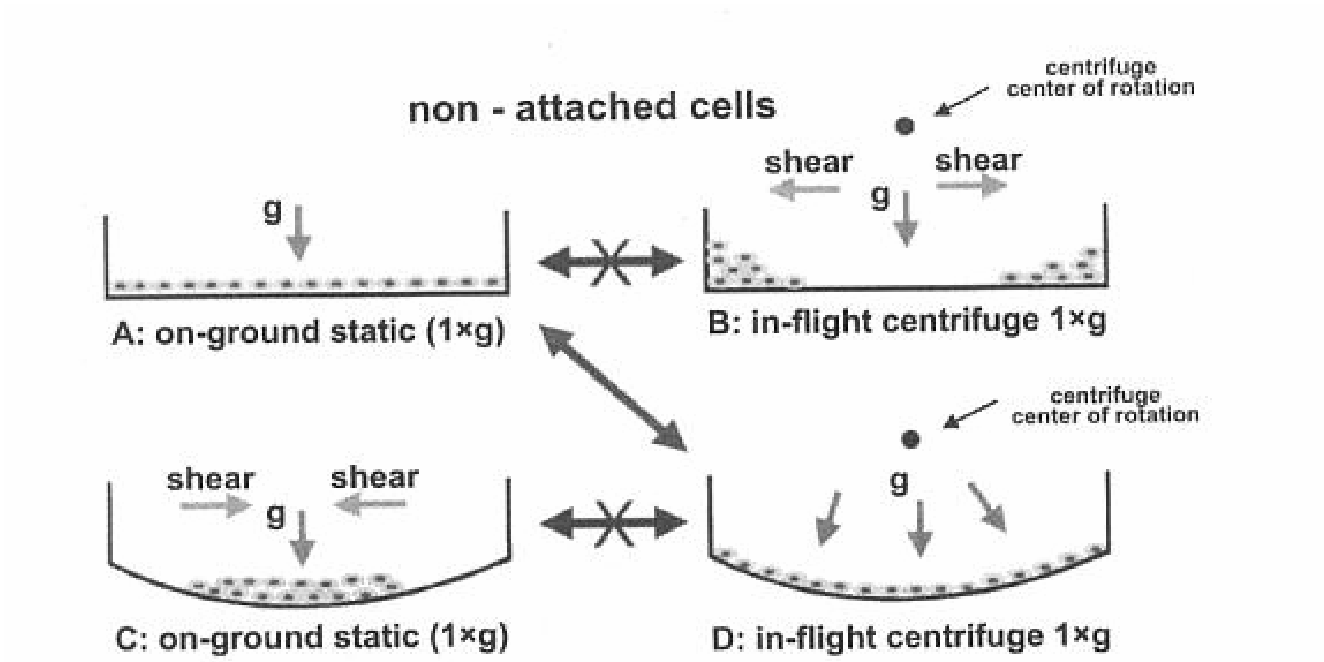




Centrifuge Free Fall Machine at the Centre for Construction and Mechatronics in Nuenen, the Netherlands, prior to delivery to the BioCentrum of the University of Amsterdam.

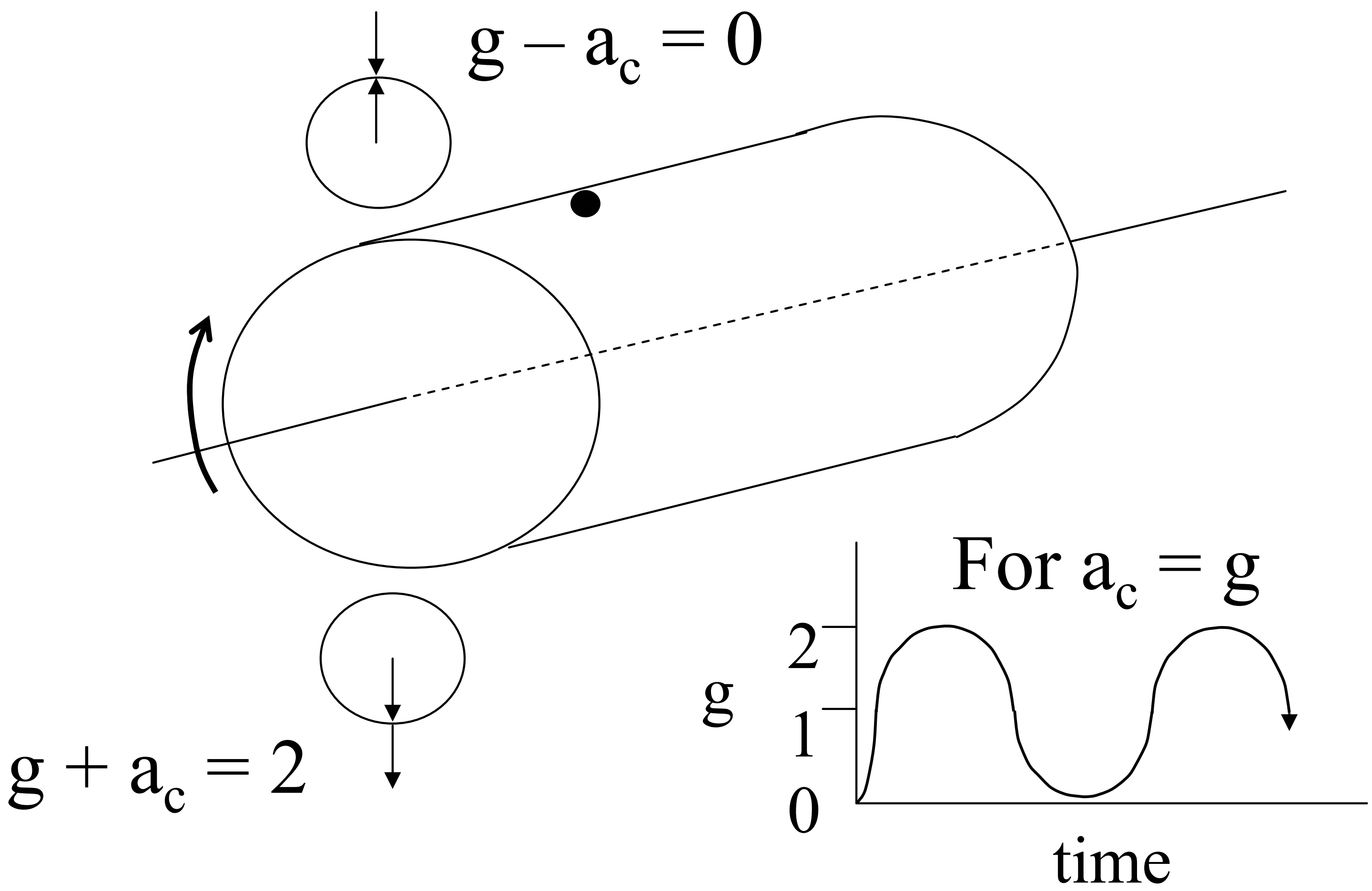
http://esapub.esrin.esa.it/microgra/micrv9n1/mesv9n1.htm

Inertial Shear



van Loon JJ, Folgering EH, Bouten CV, Veldhuijzen JP, Smit TH., Inertial shear forces and the use of centrifuges in gravity research. What is the proper control?, J Biomech Eng. 2003 Jun;125(3):342-6.

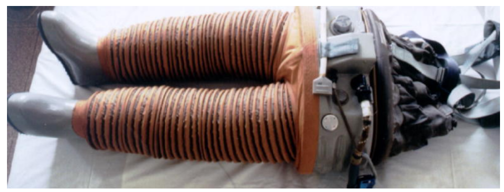
(A clinostat makes an interesting centrifuge)



Other 'Simulations' of Gravity in Space

LBNP (NASA / NASDA Photo)
Photo No:IML-2-161CD2860-058

Lower Body Negative Pressure (LBNP)
~50 mm Hg vac = ~1/2 normal BP
· Cardiovascular Deconditioning
· Post-flight Orthostatic Intolerance



Chibis Suit

G-Suits
Russian Penguin suit used on orbit – tonic stressor
G-suit used for reentry in Orbiter – orthostatic intolerance
Elastic garment - Russian KARKAS Reentry Suit

Penguin Suit

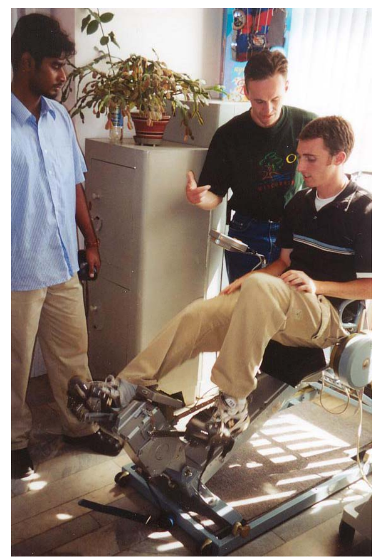
Electrostimulation (muscle)

Exercising in Weightlessness

Treadmill w/ Vibration Isolation & Stabilization (TVIS)

Cycle Ergometer w/ Vibration Isolation & Stabilization (CEVIS)

Isolated Resistive Exercise Device (IRED)



Artificial gravity in Space

How much is enough? -- 1g, 1/2 g, 1/3 g, 1/6 g…
How long is long enough? -- Continuous? Part time? Exercise duration? During sleep?

How can gravity be simulated? Point Source vs. Body Force

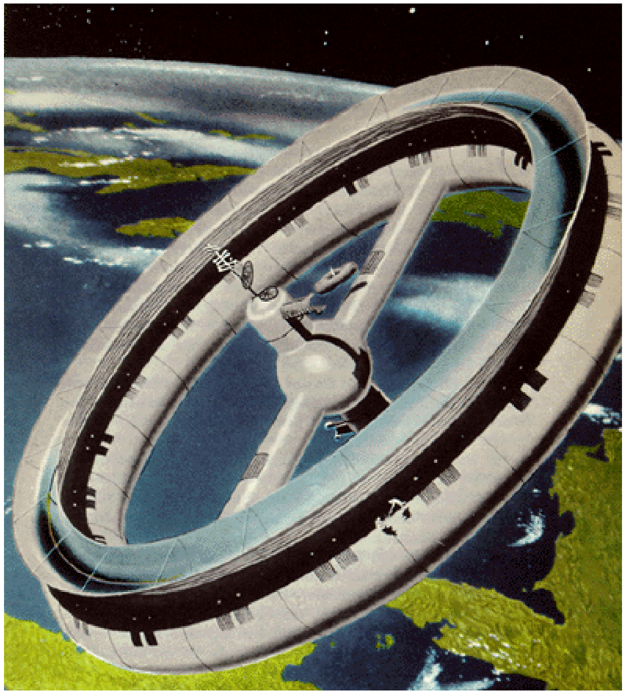
- Point Source - bungee, magnetic shoes (?)
- Body Force – acceleration, magnetism

Rotation Induced Artificial Gravity Environment (centrifugation / centripetal acceleration)

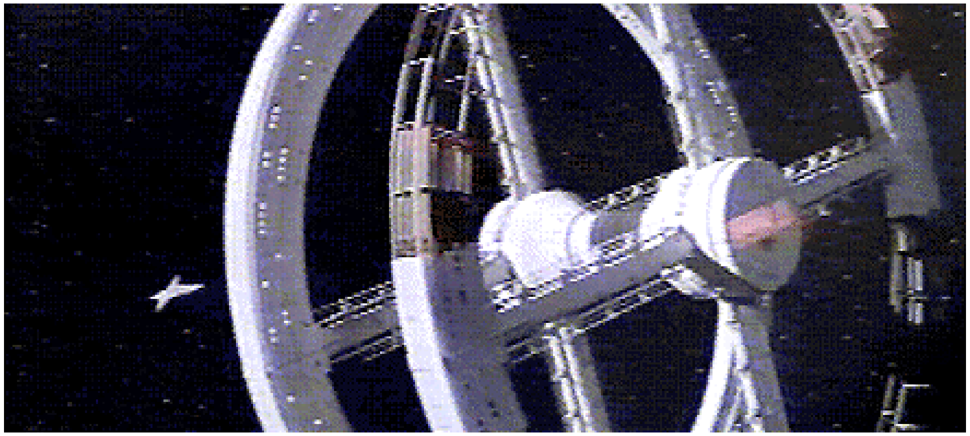
What are the tradeoffs?

- Variable-g levels / g-gradients
- Coriolis force and cross-coupled angular acceleration
- Mechanical / structural issues
- Mass / cost / complexity / need / physiological issues

Back to the Future?



Wernher von Braun's 1952 concept for a rotating space station (75 meters in diameter) designed to rotate once around its axis every 22 seconds to create a centrifugal power equivalent to a third of the Earth's gravity.



Space One from "2001 - A Space Odyssey" by Arthur C. Clarke written after the motion picture "2001" by Stanley Kubrick in 1968.