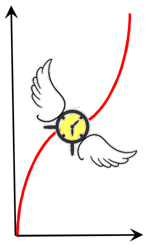
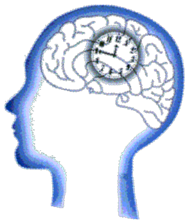
Synchronisierte Uhren, Selbstorganisation und Emergenz:

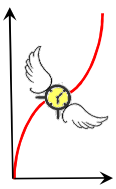


Experimente und Modelle universeller Phänomene

Harmon. Oszill. & Resonanz: curricularer Standard
Synchronisationsphänomene: ??



Manfred Euler
euler@ipn.uni-kiel.de



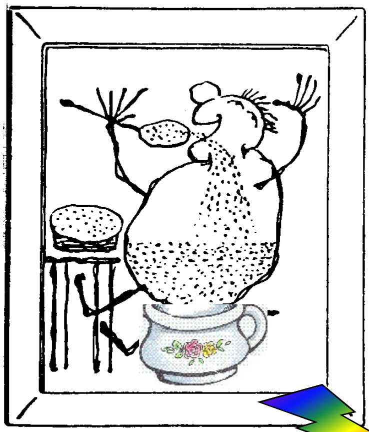
We are all of us clocks whose faces tell the passing years.

Eddington.

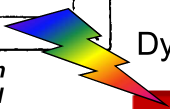
Experimente zur Uhrensynchronisation und universelle Modelle

- Selbstorganisation am Beispiel selbsterregter Oszillatoren
- Universelle Synchronisation: eine subjektive Auswahl von Experimenten
- Das Adler-(Kuramoto) Modell: Komplexitätsreduktion auf Phasenmodulation
- Synopse numerischer, analytischer, geometrischer und intuitiver Zugänge
- Synchronisation von de Broglies Uhren:
  quasi-relativistische Dynamik in einem klassischen „Spielzeugmodell“
- Ausblick (Phil.-Kog.Psych.-Päd.) – Neues erschließen:
  Kreativität und die Interaktion komplementärer Wissensformen
  „Toy models as engines of intuition“

Das innere Walten der Natur



Wilhelm Busch
Maler Klecksel



Wie entgeht Lebewesen dem

Tod (biologisch) ?

Gleichgewicht (physikalisch)?

Wesentliche Ergänzung:

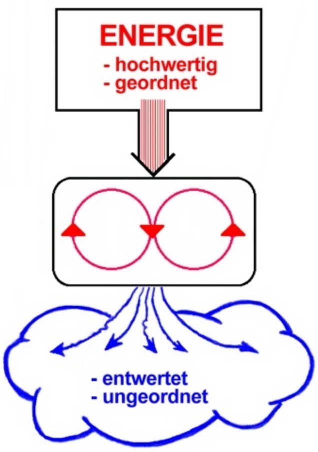
Offenes System

Im- & Export
(Materie, Energie, Entropie)

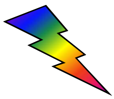
Dynamisches Gleichgewicht

Selbstorganisation

Komplexe Dynamik in offenen Systemen



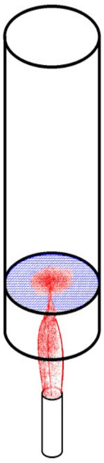
Emergenz neuer
Eigenschaften



Selbstorganisation
Leben
Wahrnehmen
Kognitive Prozesse

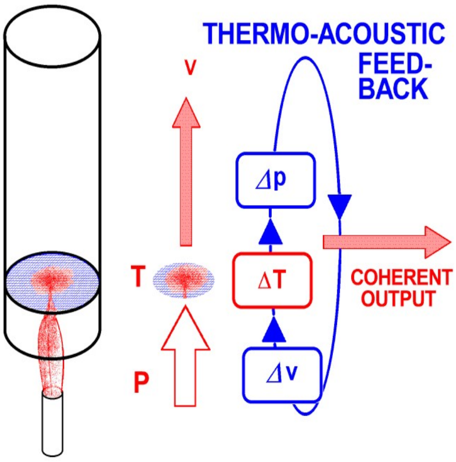
A thermo-acoustic model:

The sounds of self-organization

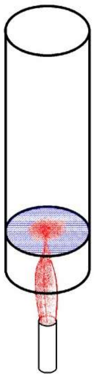


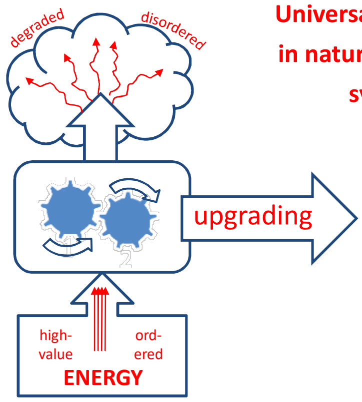
The sounds of self-organization

A thermo-acoustic laser analogue



Rijke-tube - a model for self-organization

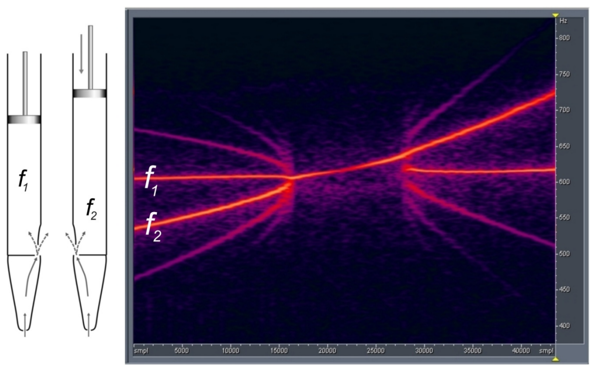




Universal phenomena in natural & designed systems:

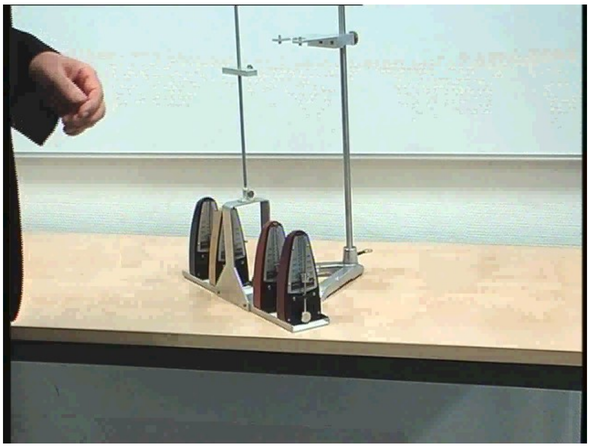
- order
- coherence
- useful work
- force
- motion
- information
- perception & cognition

Coupled acoustic self-oscillations

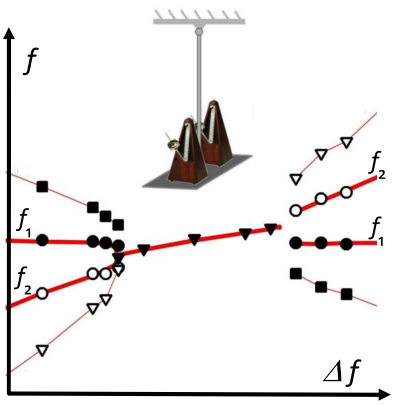


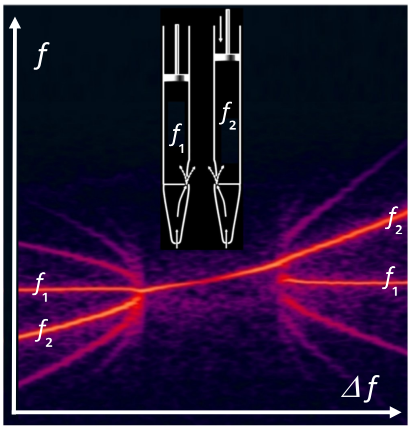
Mutual synchronization of 2 organ pipes

Synchronization of pendulum clocks (metronomes)

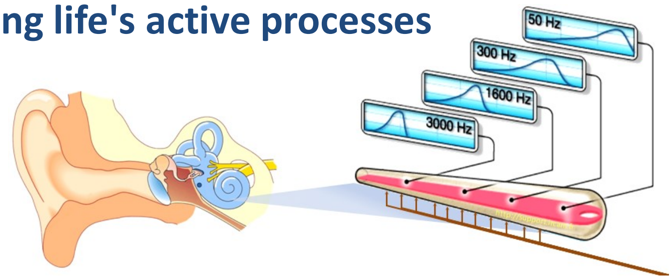


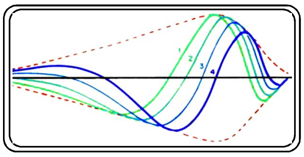
Universal bifurcation patterns (hard/soft) & coupling products (f_{comb})



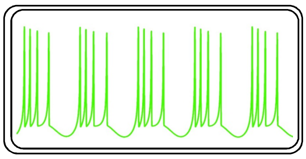


Experiments in hearing: exploring life's active processes





Dual coding of sound signals

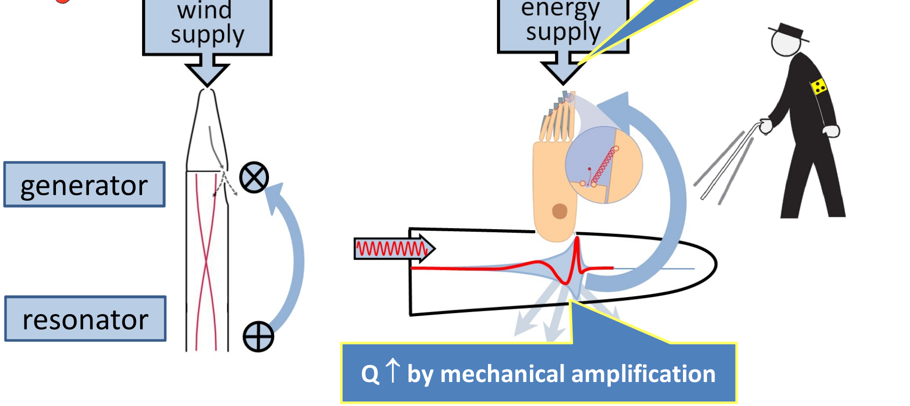


- Spectrum via travelling waves
- Amplification by feedback
- Place principle: $f \leftrightarrow x$

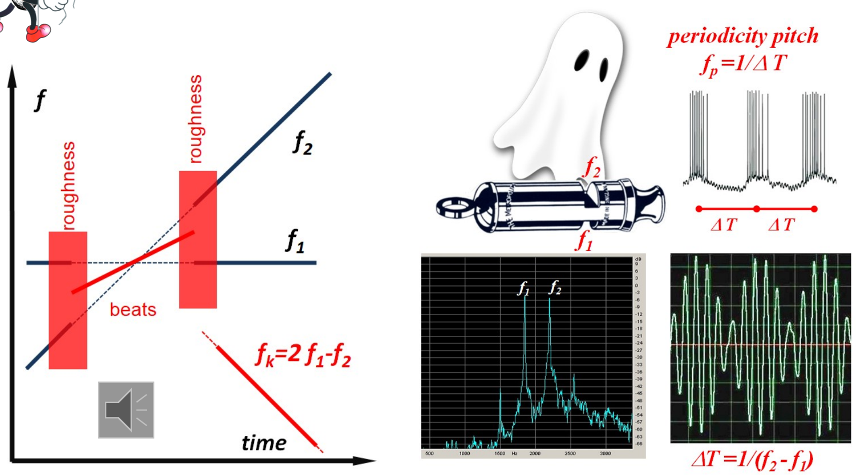
Both processes include synchronization

- Neural timing
- Rate & phase code
- Periodicity pitch: $f \leftrightarrow 1/\Delta t$

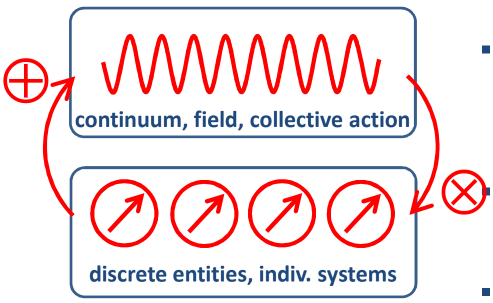
Self-organization & active hearing: organ pipe analogy



Emergent ghosts of self-organization: audible dynamical products



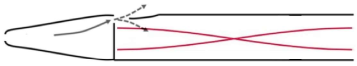
Self-organization, synchronization & coherence: Insights from a toy model



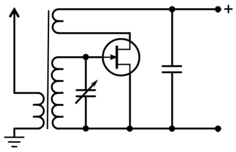
- Emergence
  - New level – new behavior
  - Coherence, dynamical rigidity
  - System acts as a whole (N vs. $N^{1/2}$)
  - Emergent effective laws
- Universality
  - Insensitivity to microscopic details
  - Multiple models
  - Protection (upper-lower level)
- Complementary principles
  - Linear versus nonlinear
  - Discrete versus continuous
- Causation/feedback across level
  - Bottom up
  - Top down

Theoretical approaches to Sync: Exercises in model order reduction

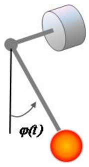
- Continuous systems: nonlinear PDE

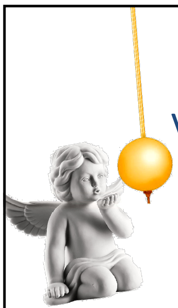


- Discrete systems: nonlinear ODE (2nd order)



- Further approximations: nonlinear ODE (1st order) for angle



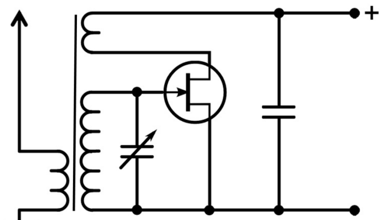


From resonance to sync: van der Pol oscillator as basic model

Overcoming friction: phase dependent energy input

$$\ddot{x} + \varepsilon(x^2 - 1)\dot{x} + \omega_0^2 x = F \sin \omega_d t$$

Driven version first studied in radio engineering

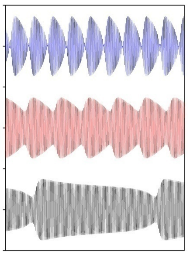


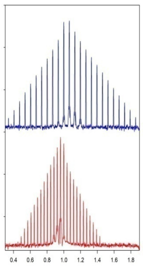
regenerative receiver

Technical:
regenerative audion receiver
Historical:
notorious propaganda machine

Driven VDP: numerical integration

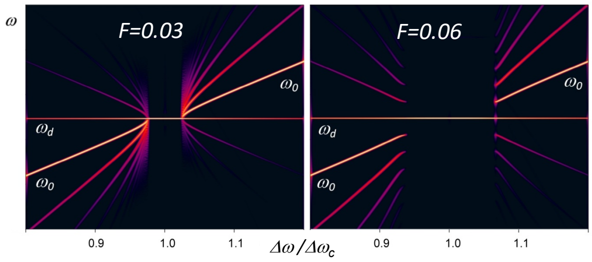
typical beat signals



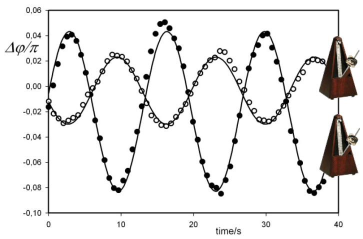


comb-spectra

spectro-grams
ε=0.1
ω_0-sweep

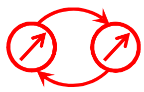


Model order reduction: An intuitive guess of the Adler equation



$$\frac{d\varphi}{dt} = \Delta\omega - B\sin\varphi$$

- Symmetric coupling of 2 metronomes
  - Faster clock is slowed down
  - Slower clock is speeded up
  - Periodic frequency pulling



- free running oscillators:
  phase rate $d\varphi/dt = \Delta\omega = \omega_0 - \omega$
- coupling adds periodic phase modulation term $\propto - \sin(\varphi)$

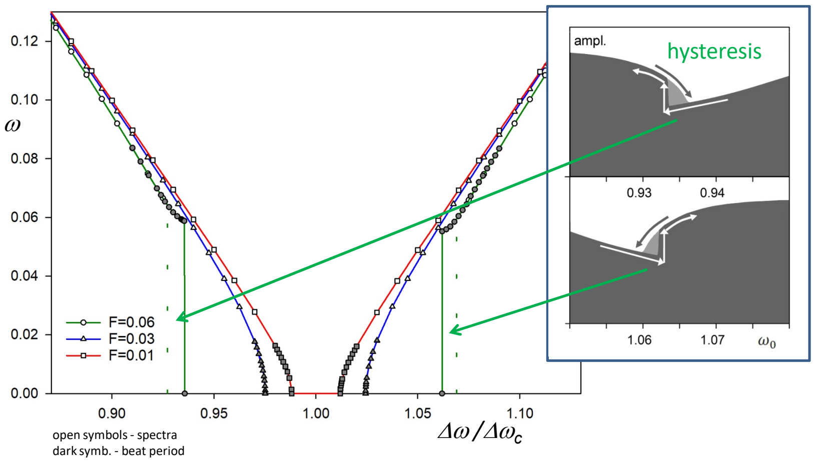
Model order reduction: formal approaches

- Derivation for electronic oscillators: Adler (Proc. IRE 1946) $$\frac{d\varphi}{dt} = \Delta\omega - \Delta\omega_c \sin\varphi$$
- Different time scales ⟹ averaging (Krylov, Bogoliubov) discards fast oscillations keeps slow modulation terms: $$x(t)=a(t)\sin\big(\omega t + \varphi(t)\big)$$
- Reduced equations ⟹ coupled amplitude and phase modulation (ε & F small, $\omega_0 \cong \omega$, A=amplitude HO):

$$\boxed{\frac{da}{dt} = \frac{\varepsilon A}{2}\left(1 - \frac{A^2}{4}\right) + \frac{F}{2\omega}\sin\omega t}$$ $$\boxed{\frac{d\varphi}{dt} = (\omega_0 - \omega) - \frac{F}{2A\omega}\cos\varphi}$$

Complex behavior of driven VDP-oscillator: locking, suppression, hysteresis, chaos

Order in complexity: Adler equation fits in the weak driving limit r & b

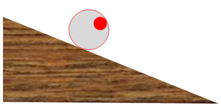


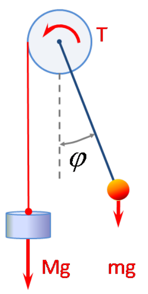
Making phase modulation tangible: A synopsis of different approaches/tools

- Numerical models
- Many possibilities and tools
- Example table calculation (Sigma Plot)
- Simple algorithm - straightforward iteration loop (VDP):

```
to=cell(2,1) ao=cell(2,2) vo=cell(2,3) so=cell(2,4)
  tn=to+dt
  an=-om0^2*sa+eps(1-sa^2)*va +F*cos(tn*omd)
  vn=va+an*dt
  sn=sa+va*dt
cell(2,1)=tn cell(2,2)=an cell(2,3)=vn cell(2,4)=sn
```

Making phase modulation tangible: Analogue mechanical models



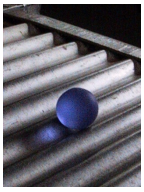


- Asymmetric cylinder on inclined plane
- Pendulum driven by constant torque
- Both with strong viscous friction
- Neglect inertial effects

$$\boxed{\cancel{I\ddot{\varphi}}+}\,\beta\dot{\varphi} + mgl\sin\varphi = T$$

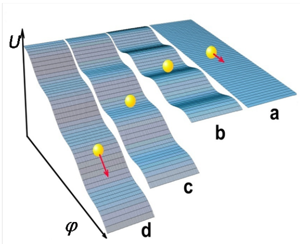
$$\dot{\varphi} = \Delta\omega - \Delta\omega_c \sin\varphi$$

Making phase modulation tangible: Energy landscape models



Washboard model

Skiing moguls (bumps)



- Motion of a 'phase particle' in potential
  $U(\varphi) = -\Delta\omega \cdot \varphi + \Delta\omega_c \cdot \sin(\varphi)$
- inclined plane with sinusoidal ripples
- Detuning $\Delta\omega$ ↔ inclination
- Coupling strength ↔ amplitude of ripples
- Phase rate in strong viscous friction:

$$\boxed{\frac{d\varphi}{dt} = -\frac{dU}{d\varphi} = \Delta\omega - \Delta\omega_c \cos\varphi}$$

Making phase modulation tangible: Analytical solution of Adler equation

- With $\gamma = \frac{\Delta\omega}{\Delta\omega_c}$ & $\Delta\omega_c = \omega_0$ & separation: $\boxed{\int \frac{d\varphi}{\gamma - \cos\varphi} = \int \omega_0 \, dt}$
- Integration somewhat tedious,
  with Weierstrass substitution: $\tan\frac{\varphi}{2} = u$, $d\varphi = \frac{2du}{(1+u^2)}$, $\sin\varphi = \frac{2u}{1+u^2}$, $\cos\varphi = \frac{1-u^2}{1+u^2}$

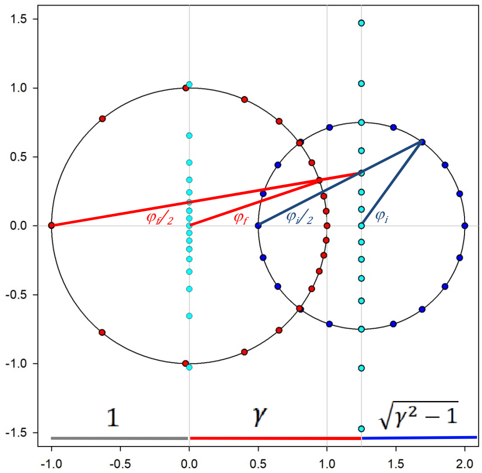
$$\tan\frac{\varphi}{2} = \frac{\gamma - 1}{\sqrt{\gamma^2 - 1}} \tan\left(\frac{\omega_0\sqrt{\gamma^2 - 1}}{2} t\right)$$

$$\boxed{\varphi = 2\tan^{-1}\left(\frac{\gamma - 1}{\sqrt{\gamma^2 - 1}} \tan\left(\frac{\omega_0\sqrt{\gamma^2 - 1}}{2} t\right)\right)}$$

- *tan(φ/2)* substitution ⇒ stereographic projection of circle to a line
- The world's "sneakiest substitution" (Spivak) – helps to crack important integrals
- Sneaky math opens up rich physics from cartography to relativity
- Mapping of initial angle to final angle – re-parametrize time
- Dynamical geometry:
  "tangible" visualization

$$\boxed{\tan\left(\frac{\varphi_f}{2}\right) = \frac{\gamma - 1}{\sqrt{\gamma^2 - 1}} \tan\left(\frac{\varphi_i}{2}\right) = \frac{\sqrt{\gamma^2 - 1}}{\gamma + 1} \tan\left(\frac{\varphi_i}{2}\right)}$$

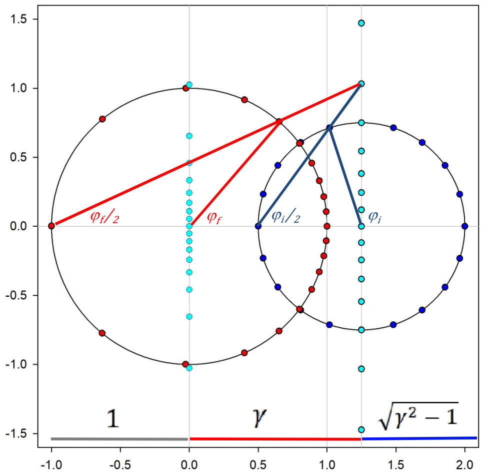
Making phase modulation tangible: A geometric representation of half angle trsf.



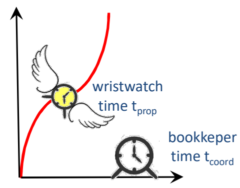
- the strange “cogs of sync”
- continuous gear, periodical
- reparametrize time – obtain phase rate via geometry
- 2 different phase rates

$$\tan\left(\frac{\varphi_f}{2}\right) = \frac{\sqrt{\gamma^2-1}}{\gamma+1}\tan\left(\frac{\varphi_i}{2}\right)$$

Making phase modulation tangible: A geometric representation of half angle trsf.

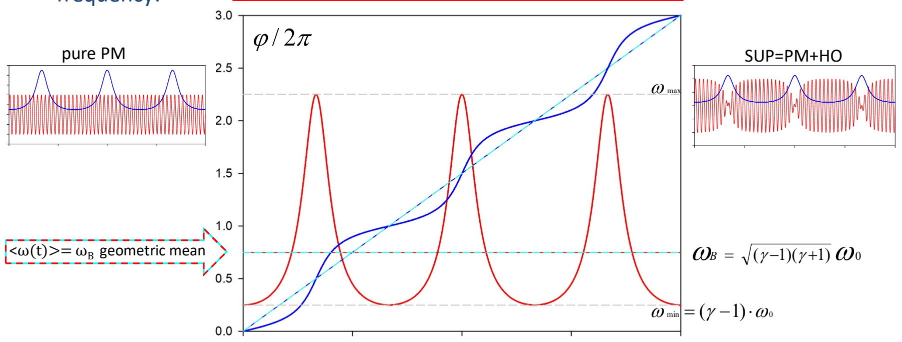


- the strange “cogs of sync”
- continuous gear, periodical
- reparametrize time – obtain phase rate via geometry
- 2 different phase rates
- key to SRT models
- 2 clocks: t_{prop} - t_{coord}



Phase modulation & instantaneous frequency

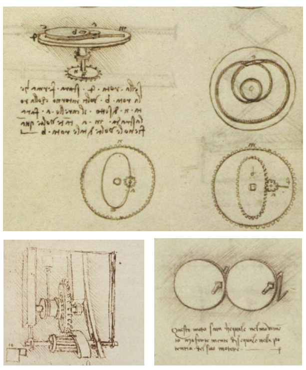
- Phase $$\varphi = 2\tan^{-1}\left(\frac{\gamma-1}{\sqrt{\gamma^2-1}}\tan\left(\frac{\omega_0\sqrt{\gamma^2-1}}{2}t\right)\right)$$
- Phase rate = instantaneous frequency: $$\dot{\varphi} = \frac{(\gamma^2-1)\omega_0}{\gamma+\cos\left(\sqrt{\gamma^2-1}\cdot\omega_0 t\right)} = \omega(t)$$



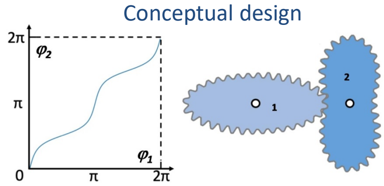
From Physics to Mechanical Technology:

A creative design exercise: CVT to simulate phase rate in sync

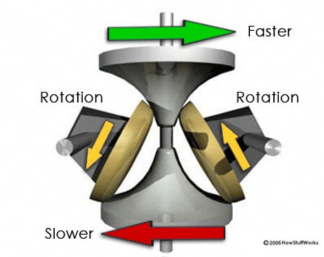
Basic ideas: Leonardo da Vinci



Conceptual design

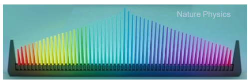


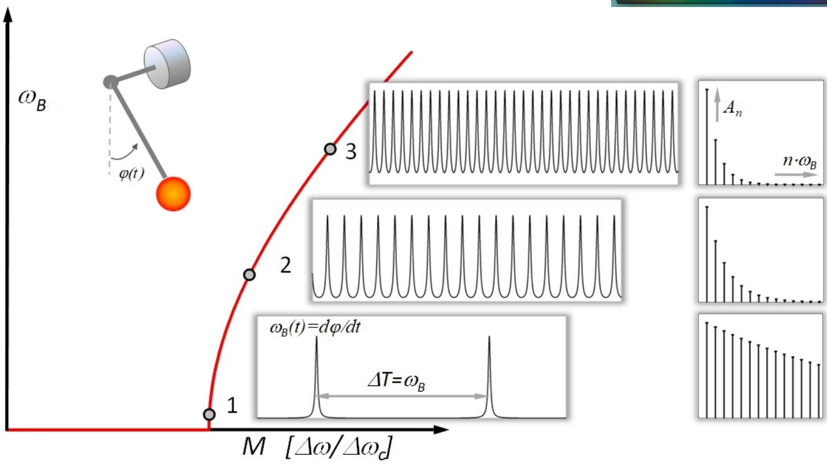
Applications

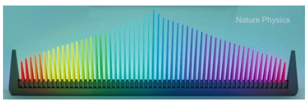


The creative leap from mechanical gears to gears & rulers of Quantum Technology

Beats & comb-spectra







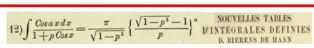
Comb spectra: a largely elementary analysis

Use ‘relativistic’ notation

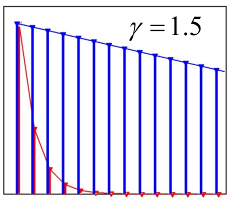
$\gamma = \frac{1}{\sqrt{1-\beta^2}}, \quad \beta\gamma = \sqrt{\gamma^2-1}$

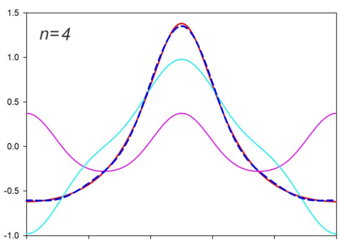
$$\boxed{\dot{\varphi} = \frac{(\beta\gamma)^2\omega_0}{\gamma + \cos(\omega_B t)}, \quad \omega_B = \beta\gamma\omega_0}$$

$$\boxed{\dot{\varphi} - \beta\gamma = \sum_n (-R)^n \cdot 2\beta\gamma \cdot \cos(n \cdot \omega_B t)}$$



Fourier series expansion





$$\boxed{R = \gamma - \beta\gamma}$$

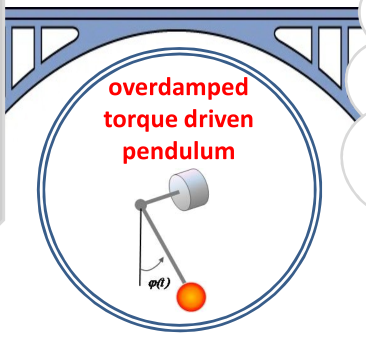
Universal coherence:
Bridging classical and quantum domains

Analogies on the level of emergent variables

Self-oscillations: a cross-cutting theme in classical systems

- Physics
- Technology
- Chemistry
- Life Sciences

a "toy" system



Self-oscillations and coherence in quantum systems

- Laser, Maser
- Josephson oscillations in coupled quantum condensates
- Emerging quantum technologies
- Metrology
- Quantum computing

\+ … ideas to come

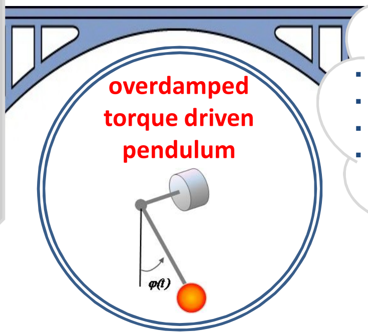
Extending the model even further :
From Sync to relativistic particle dynamics & QFT

Concrete models

Self-oscillations: a cross-cutting theme in classical systems

- Physics
- Technology
- Chemistry
- Life Sciences

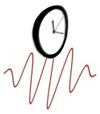
Does the toy model work? If yes, why?



Abstract approaches

Self-oscillations, coherence & relativistic effects

- Sync & de Broglie's clocks
- From kinematics to dynamics
- What is a particle in QFT
- Accelerated systems and relativistic paradoxa



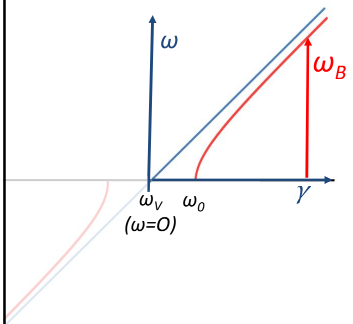
The cornerstone of QT: matter waves & moving clocks - de Broglie's basic ideas

- A (massive) particle is a clock: $E_0 = \hbar\, \omega_0$
- Beat of clock ⇔ particle mass: $\omega_0 = mc^2/\hbar$
- The puzzling result: different relativistic transforms of
  - Apparent "relativistic" mass increases $M = m\,\gamma$
  - Clock rate decreases, time dilation $\omega = \omega_0 / \gamma$

- Kinematic solution of puzzle:
  matter waves with $\lambda_B = h/p$ in phase with particle clock (Diss. de Broglie)
- De Broglie's "Law of phase harmony" ↔ Lorentz invariance of phase
- Relativistic dispersion: $E=((pc)^2+(E_0{}^2)^2)^{1/2}$, $v_g=dE/dp$, $v_{ph}=p/E$, $v_g v_{ph}=c^2$

- Kinematics leaves open possible mechanisms
- Puzzle can be solved also by "real" dynamics: sync model

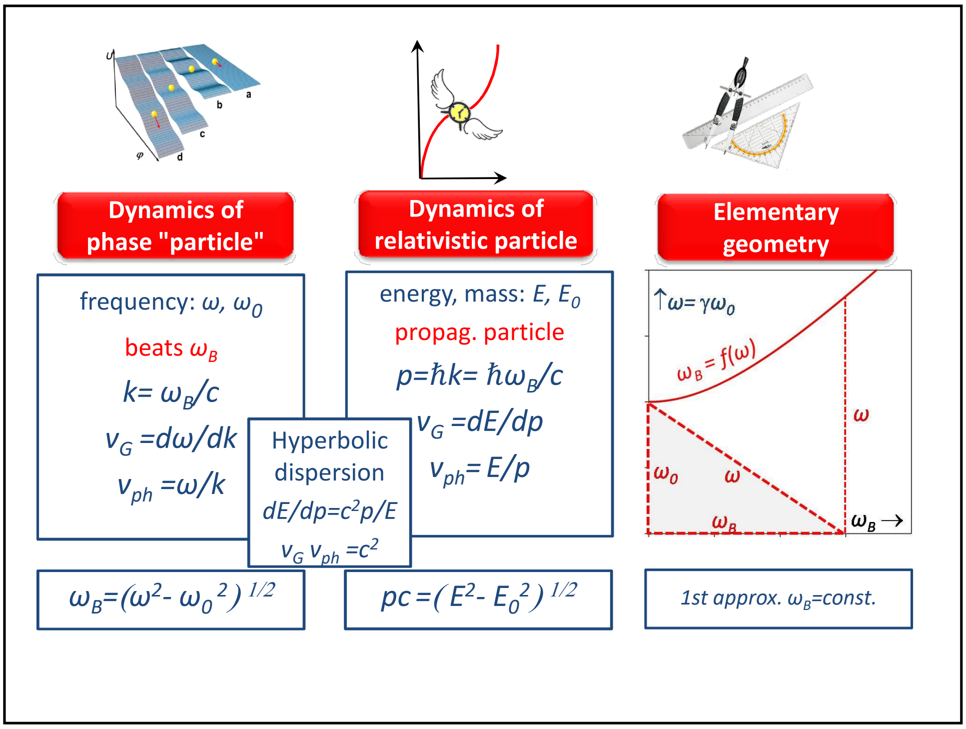
Synchronizing de Broglie's clocks - from kinematics to dynamics



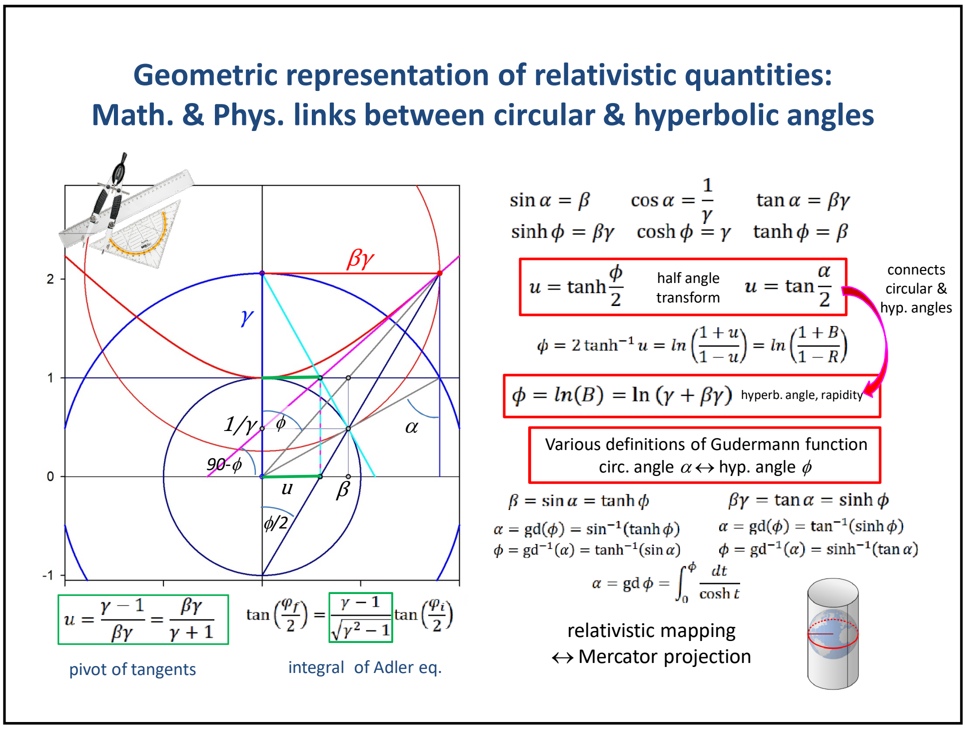
- Sync provides a dynamical model
- Particle: clock running forever ⇒ $Q=\infty$
- Dynamical model: self sustaining oscillator (ω_0)
- $E=\hbar\omega_0$ energy threshold to create excitation
- Particle clock interacts with background field ω_V - resonates actively with vacuum
- Dynamics depends on boosted frequency ω
  - For $\omega < \omega_0$ $(\gamma<1)$ ⇔ no excited state
  - For $\omega > \omega_0$ $(\gamma>1)$ ⇔ *excitation in motion*, beats
  - Beat frequency : $\omega_B = (\omega^2 - \omega_0{}^2)^{1/2} = \beta\,\gamma\,\omega_0$

Correspondence rules:
(de Broglie frequency – not a common notion!)

- Particle ⇔ excitation on a sea of energy (cf. Dirac)
- $E = \hbar\omega = \hbar\gamma\,\omega_0$
- $p = \hbar k = \gamma\, mv = \beta\gamma\, mc = \hbar\omega_B/c = h/\lambda_B$
- $\lambda_B/\lambda_0 = 1/\beta\gamma$ $\omega_B/\omega_0 = \beta\gamma$;



Dynamics of phase "particle"
Dynamics of relativistic particle
Elementary geometry
frequency: ω, ω_0
beats ω_B
$k = \omega_B/c$
$v_G = d\omega/dk$
$v_{ph} = \omega/k$
Hyperbolic dispersion
$dE/dp = c^2p/E$
$v_G\, v_{ph} = c^2$
energy, mass: E, E_0
propag. particle
$p = \hbar k = \hbar\omega_B/c$
$v_G = dE/dp$
$v_{ph} = E/p$
$\uparrow \omega = \gamma\omega_0$
$\omega_B = f(\omega)$
ω
ω_0
ω
ω_B
$\omega_B \rightarrow$
$\omega_B = (\omega^2 - \omega_0^2)^{1/2}$
$pc = (E^2 - E_0^2)^{1/2}$
1st approx. ω_B=const.



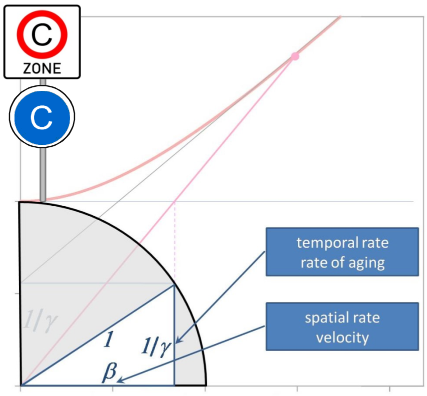
Geometric representation of relativistic quantities:
Math. & Phys. links between circular & hyperbolic angles
$\beta\gamma$
γ
$1/\gamma$
ϕ
α
$90\text{-}\phi$
u
β
$\phi/2$
2
1
0
-1
$\sin\alpha = \beta \quad \cos\alpha = \frac{1}{\gamma} \quad \tan\alpha = \beta\gamma$
$\sinh\phi = \beta\gamma \quad \cosh\phi = \gamma \quad \tanh\phi = \beta$
$u = \tanh\frac{\phi}{2}$ half angle transform $u = \tan\frac{\alpha}{2}$
connects circular & hyp. angles
$\phi = 2\tanh^{-1}u = ln\left(\frac{1+u}{1-u}\right) = ln\left(\frac{1+B}{1-R}\right)$
$\phi = ln(B) = \ln(\gamma + \beta\gamma)$ hyperb. angle, rapidity
Various definitions of Gudermann function
circ. angle $\alpha \leftrightarrow$ hyp. angle ϕ
$\beta = \sin\alpha = \tanh\phi \quad \beta\gamma = \tan\alpha = \sinh\phi$
$\alpha = \mathrm{gd}(\phi) = \sin^{-1}(\tanh\phi) \quad \alpha = \mathrm{gd}(\phi) = \tan^{-1}(\sinh\phi)$
$\phi = \mathrm{gd}^{-1}(\alpha) = \tanh^{-1}(\sin\alpha) \quad \phi = \mathrm{gd}^{-1}(\alpha) = \sinh^{-1}(\tan\alpha)$
$\alpha = \mathrm{gd}\,\phi = \int_0^\phi \frac{dt}{\cosh t}$
$u = \frac{\gamma-1}{\beta\gamma} = \frac{\beta\gamma}{\gamma+1}$
$\tan\left(\frac{\varphi_f}{2}\right) = \frac{\gamma-1}{\sqrt{\gamma^2-1}}\tan\left(\frac{\varphi_i}{2}\right)$
pivot of tangents
integral of Adler eq.
relativistic mapping
$\leftrightarrow$ Mercator projection

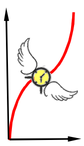
Sync - a model for dividing up total energy between:

- energy & momentum
- temporal periodicity & spatial periodicity
- rate of time (clock rate, rate of aging) & the rate of space (velocity)

Every object's spacetime rate is c:
c is limiting rate
as well as commanded rate

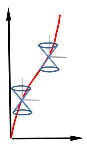
Beyond the simplicity of ω_B=*const*:
- Sync & acceleration
- Opens up the Pandora box of relativistic paradoxa/puzzles
- Micro-version of twin travels
- Tools provide access to further puzzles in extended systems (Bell spaceships, Born rigidity)
- $\Rightarrow$ window to GRT





minimalist particle model:

clock moving along a parameterized timelike curve

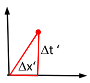


Conceptual refinements of sync-model:
Accelerating clocks

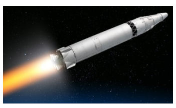
- Acceleration can be handled in SRT
- Use sequence of instantaneous frames co-moving with accel. particle
- Apply differential Lorentz transformation (Rindler)

$$dx' = \gamma(dx + v\,dt),\ \ dt' = \gamma(dt + v dx/c^2)$$

$$dx = 0, c = 1 \ \rightarrow \boxed{dx' = \beta\gamma\,dt,\ \ dt' = \gamma\,dt}$$



Interpretation of resulting relations in terms of one map – two clocks:
- *dt* – proper time, *dt'*- coordinate time
- Map distance covered in proper time $\quad x(t) \propto \int \beta\gamma(t)\,dt$
- Elapsed coordinate time $\quad t_{co} \propto \int \gamma(t)\,dt$
- Proper velocity (momentum/mass) $\quad v_{prop} = \beta\gamma(t)$
- Unusual notion $\Rightarrow$ common in rocket engineering and space flight
- v_{prop} not limited, α_{prop} links relativistic acceleration with N2
- Force felt by accelerated observer: $F=m\alpha_{prop}$



Summary of math & phys. meaning *($t_{pr}=\tau$, $t_{co}=t$, include c)*

$\overrightarrow{v_{co}} = \dfrac{\overrightarrow{dx}}{dt}$ $\qquad \gamma = \dfrac{dt}{d\tau}$ $\qquad \vec{a} = \dfrac{d\vec{v}_{co}}{dt}$ cordinate acceleration

$\overrightarrow{v_{pr}} = \dfrac{\overrightarrow{dx}}{d\tau} = \gamma\dfrac{\overrightarrow{dx}}{dt} = \dfrac{\vec{p}}{m}$ $\qquad \vec{\alpha} = \dfrac{d\vec{v}_{pr}}{dt} = \dfrac{d}{dt}\left(\dfrac{\overrightarrow{dx}}{d\tau}\right)$ proper acceleration α

- mixed derivatives

$d\gamma = \gamma^3\beta\, d\beta \quad d(\beta\gamma) = \gamma^3 d\beta \qquad \vec{\alpha} = \gamma^3\vec{a}$ prop. acc. α is absolute!

Meaning of proper time derivatives (1+1-dim) – 2-acceleration components:

Temporal part $\dfrac{d\gamma}{d\tau} = \gamma^3\beta\dfrac{d\beta}{d\tau} \propto A^0$ $\qquad$ Spatial part $\dfrac{d(\beta\gamma)}{d\tau} = \gamma^3\dfrac{d\beta}{d\tau} \propto A^1$

$|\alpha| = \sqrt{-(A^0)^2 + (A^1)^2} \propto \gamma^2\dfrac{d\beta}{d\tau}$ $\qquad$ Components in comoving frame $(0, |\alpha|)$

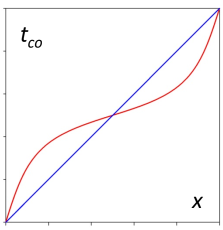
REM:
Motion changes measure of time
Acceler. changes rate of time

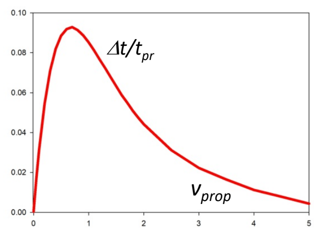
Sync: a conceptual playground to study accelerated systems in SR

- A model, how to divide up energy between spatial & temporal periodicity
- Provides us with tangible tools to explore and to acquaint with abstract concepts
- Represents an intuitive access towards more challenging notions - e.g. accelerations
- Presents a prelude to some phenomena of GRT

Sync-Model as mechanical "Spacetime Engine"

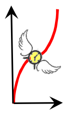
- Proper velocity – normalized phase rate (c=1) $\dfrac{\dot{\varphi}}{2\pi} = \dfrac{(\beta\gamma)^2}{\gamma + \cos(\omega_B t)} = \beta\gamma(t)$ this is t_{pr} !!!
- Covered distance $x(t) = \int \beta\gamma(t)\, dt$
- Coordinate time: no direct correspondence in model, must be calculated $t_{co} = \int \gamma(t)\, dt$





- No uniform motion, v≠const.
- Jerks on the microscale
- Explore conceptual challenge - different concepts of acceleration : coordinate-proper-temporal-spatial

- Different proper times
- Different 'rates of aging'
- Micro-version of twin paradox



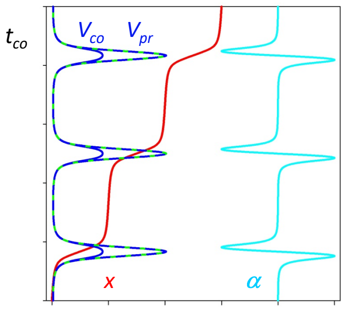
Particle in QFT: never at rest - temporal & spatial modulation

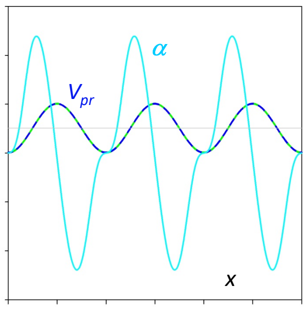
Worldline *x(t_{co})* , $\omega_0 = 2\pi$, $c=1$

- Proper velocity $v_{pr} = \beta\gamma$
- Coordinate velocity $v_{co} = \beta$
- Proper acceleration $\alpha = \dfrac{dv_{pr}}{dt_{co}}$

Compare with spatial dependence of

- Proper velocity $v_{pr}(x) = \gamma - \cos(2\pi x)$
  - harmonic washboard
- Proper acceleration $\alpha = \dfrac{d\gamma}{dx}$



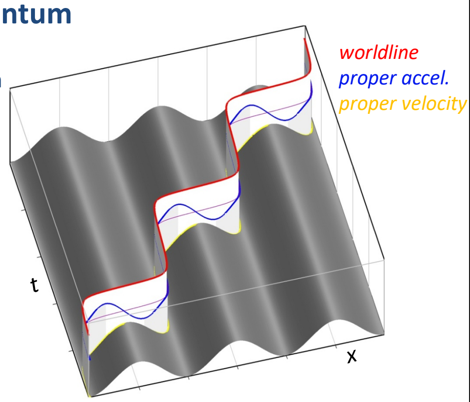


Spatial modulation of momentum: lattice model as an intuitive picture

Sync model and quasi-relativity in systems with spatial periodicity of momentum

Lattice models – periodical quasi-momentum

- Historical note:
  Heisenberg's lattice world (1930) - discarded because fixed lattice ('vacuum') is not Lorentz invariant
- Sync: emergent modulation of *p* & α
- Spatial & temporal modulation maintain Lorentz-invariance



Modern versions:

- Quasi-relativity in narrow band semiconductors
  - 2 different concepts of effective mass
- Dirac cones in graphene
- Photonic lattices, metamaterials with engineered periodicity

momentum related (v_{drift}=const). $\vec{p} = \gamma m \vec{v}$

acceleration related $\vec{F} = m\vec{a} = \gamma^3 m\vec{a}$

Why does model work?
Does it represent (which?) elements of reality?

Unable to answer comprehensively – same class of ultimate questions as
"What is a particle?"
Sync resonates with approaches from different domains & theoretical backgrounds

How massless entities become massive (Confinement-models)

- Transversal waves in elastic string ⇒ become massive by adding transversal springs
- Waveguide models
- Wave propagation in cochlea
- Photons confined in a resonator

Accelerated charged particles should radiate (the perennial problem of radiation reaction)

- Nonradiating states
- Near field effects (emission & absorption in near field, nothing emitted into far field)
- Virtual particle creation and annihilation

Acceleration and the vacuum

- Unruh-effect
- Particle creation in vacuum (particle number is not conserved)
- Radiation from accelerating mirrors – parametric oscillator models

Just for fun: Mass without mass
a (classical) taste of Higgs

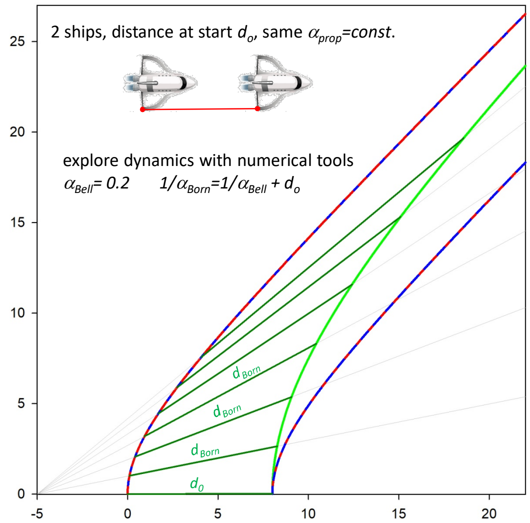
- Synchronization creates spectrum with a gap
- Emergence of rest energy $E_0 = \hbar\,\omega_c$
  & invariant rest mass analog: $m = E_0/c^2$
- Background field gives mass to massless particles: ⇒ v < c
- Classical model provides an intuition of the Higgs mechanism
- Upgrades the popular "crowd" or the "molasses" metaphor

Matter waves are fully relativistic: Implications for teaching in view of prevailing nonrelativistic introductions?

Sync model opens up a new perspective on "the cornerstone" of quantum physics: matter waves as an emergent **relativistic** phenomenon

How to teach special relativity (1976):
Bell’s spaceships as a plea for a dynamical approach

A quiz at CERN cafeteria: Does a thin thread between the spaceships break? Explain!



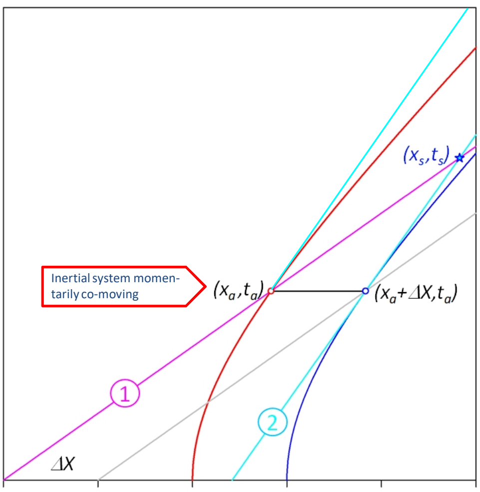
Both ships in hyperbolic motion.
- Majority vote: no break
- Bell’s conclusion: It breaks!
- Correct. ☺
- His explanation- because of “real” Lorentz contraction?

—— Simultaneity lines
- Reference to Born-rigid motion
- Born-rigidity condition $\alpha=1/d_{vertex}$
- Invariant proper distance d_{Born}
- A less philosophically loaded explanation ☺:

  It breaks, because $d_{Bell} > d_{Born}$

  - the proper length increase is ‘real’ (requires further theor. assumptions)

Algorithm for calculating ‘proper length’ in accel. systems :
Clarifies the instantaneous & local character of d_{prop}



iterate

1 $\dfrac{c(t-t_a)}{x-x_a} = \beta_a$

2 $\dfrac{c(t-t_a)}{x-(x_a+\Delta x)} = \dfrac{1}{\beta_a}$

intersect at (x_s,t_s)

$$x_s = x_a + \frac{1}{1-\beta_a^2}\Delta x$$

$$t_s = t_a + \frac{\beta_a}{1-\beta_a^2}\Delta x/c$$

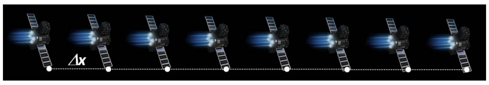
proper distance increment

$$\Delta d = \sqrt{(x_s-x_a)^2 - c^2(t_s-t_a)^2}$$

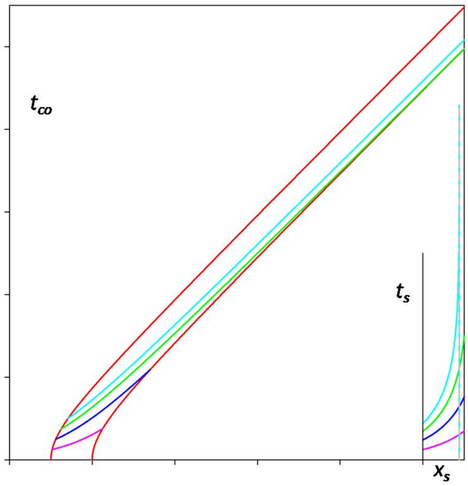
$$\Delta d = \frac{\sqrt{1-\beta_a^2}}{1-\beta_a^2}\Delta s = \gamma_a \Delta s$$

sum of increments Δd is an appropriate measure of L_{prop}

Extending the system and refining proper distance:



The accelerating space fleet



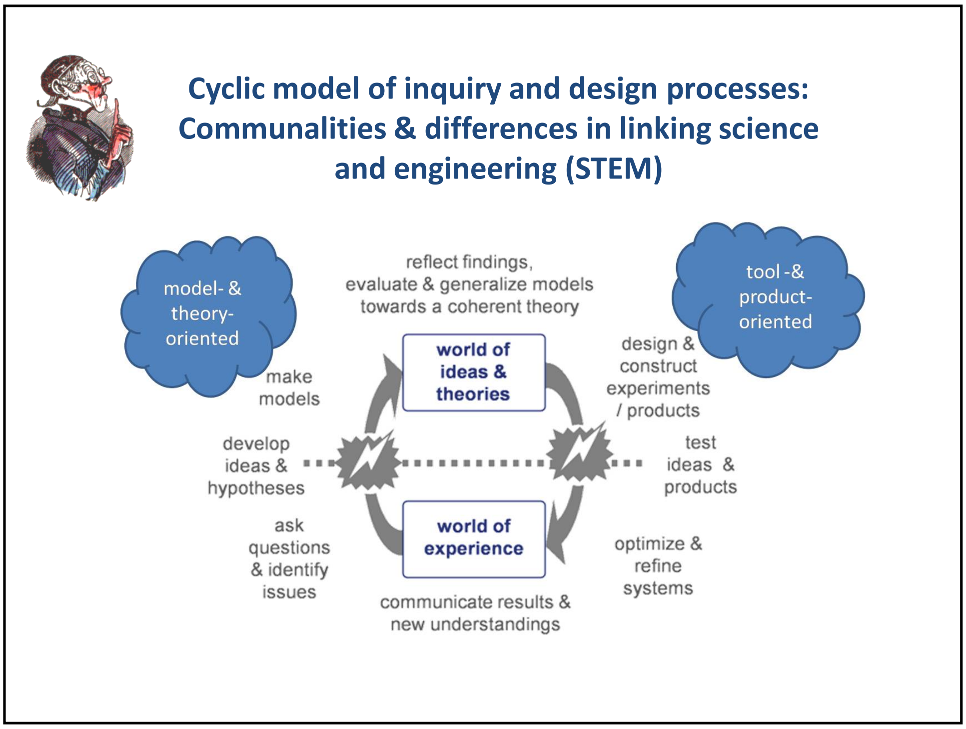
Proper distance :

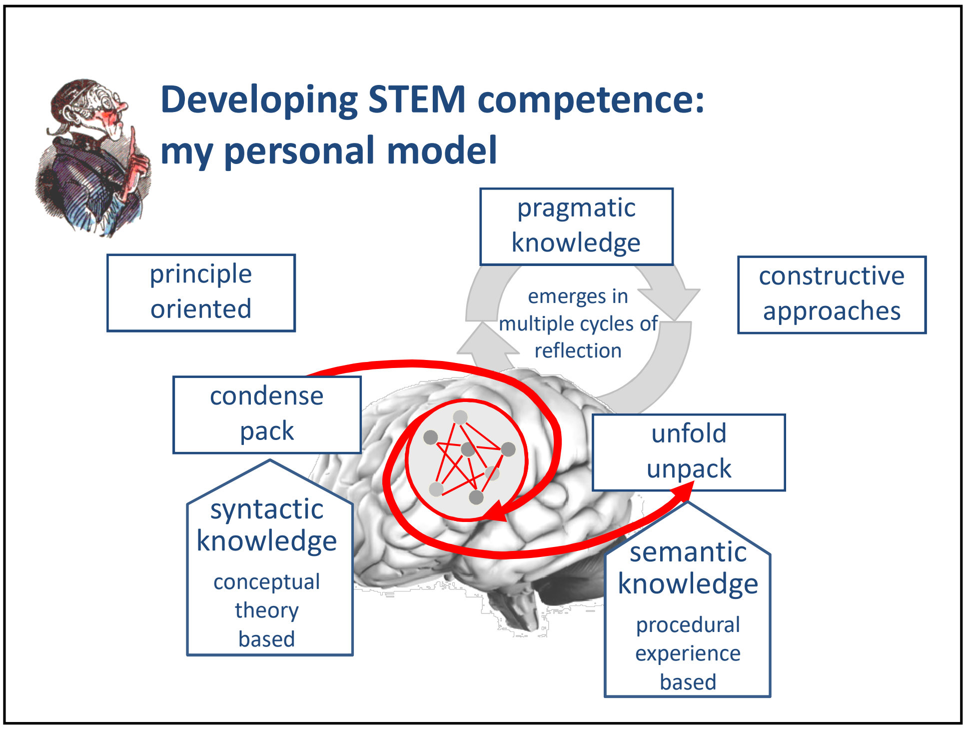
- Local concept in accelerated systems
- Clock rates differ between bow and stern
- Implications for communication?
- Depending on acceleration & time the bow becomes invisible from the stern
- A horizon emerges
- In SR, the existence of horizons in accelerated systems presents a glimpse of GRT

Outlook:
a highly personal account of guiding ideas from philosophy, cognitive science & pedagogy

The challenge of teaching, learning & doing physics

Success requires orchestrating
an intelligent interplay of complementary forms of knowing


Cyclic model of inquiry and design processes: Communalities & differences in linking science and engineering (STEM)
model- & theory-oriented
reflect findings, evaluate & generalize models towards a coherent theory
tool -& product-oriented
make models
world of ideas & theories
design & construct experiments / products
develop ideas & hypotheses
test ideas & products
ask questions & identify issues
world of experience
optimize & refine systems
communicate results & new understandings


Developing STEM competence: my personal model
pragmatic knowledge
principle oriented
constructive approaches
emerges in multiple cycles of reflection
condense pack
unfold unpack
syntactic knowledge
conceptual theory based
semantic knowledge
procedural experience based