Intuition in physics: What is a physicist anyway?

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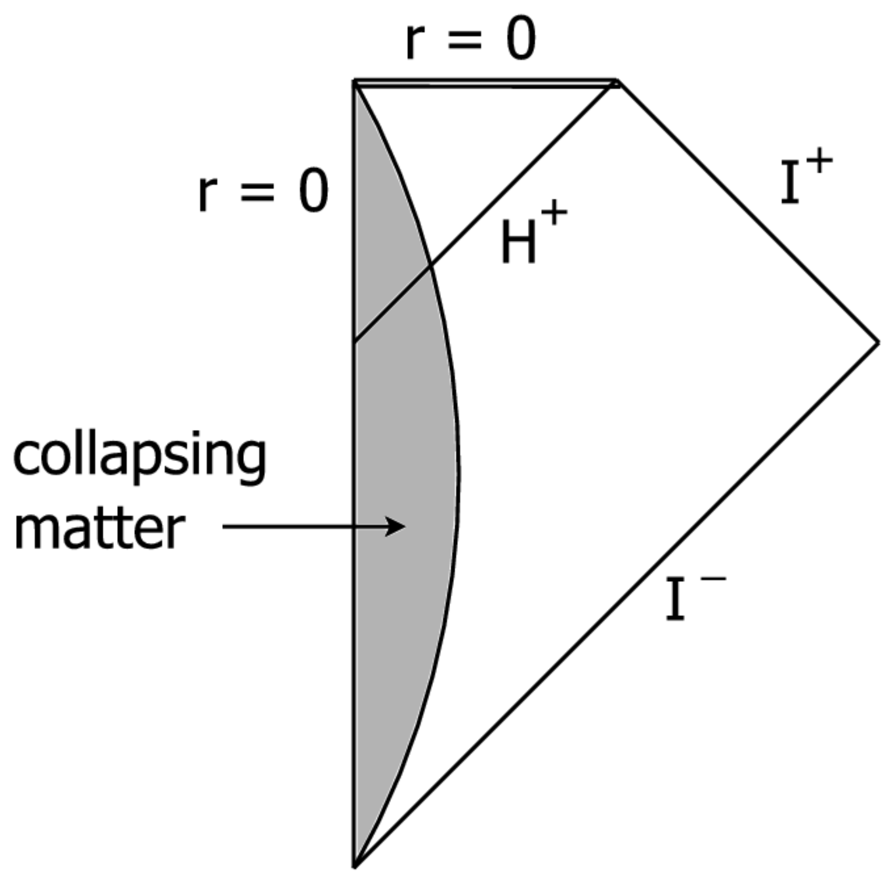
Intuition

- Many of the most admired physicists, like Feynman, had great ‘intuition’ - the ability to see an answer without doing the mathematics, and to get it right. The ability to see connections between different parts of physics.
- This is not universal among physicists, but I believe it is very desirable, and we should cultivate it in our students.
- The history of GR includes a period 1930-1950 where intuition seems to have been woefully absent, resulting in much inept mathematics. Lesson: maths normally needs guidance from good intuition.
- In this presentation I want to speculate a bit about how to understand what physics intuition really is, and how it can be encouraged — at all levels.
- First, some of my own experiences.

Coming to grips with the Kerr metric

- Period 1968-1970 was a key time for *understanding* Kerr and BHs in general.
- Penrose diagram very helpful *model* of complete spacetime.
- Putting physics into Kerr frame-dragging, ergosphere:
    - Penrose process: extracting energy and spin
    - Thorne's introduction of zero angular-momentum observers (ZAMOs) brought clarity
    - Thought experiments, like lowering a mass on a string, enriched picture.
- Goal: a faithful intuitive way to put BHs, especially Kerr, into astrophysical systems. The Kerr solution is itself a *model*, since a real BH (eg Sagittarius A*) will be somewhat distorted, not in pure vacuum, and likely accreting matter.



Stellar ergospheres are unstable - why not Kerr?

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On the ergoregion instability

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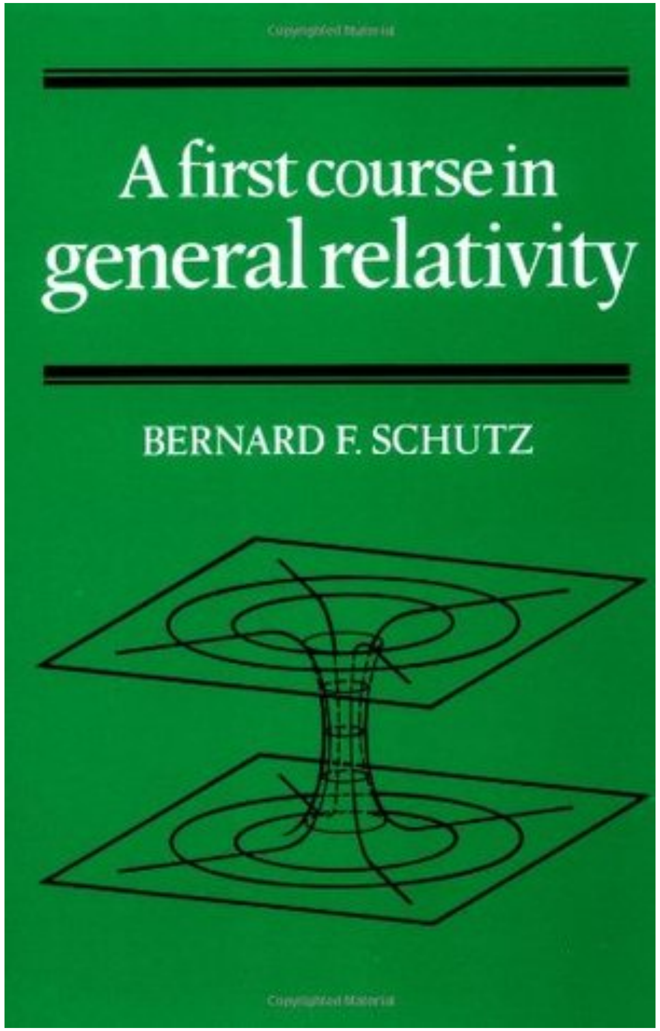
Rotating, ultra-compact stars in general relativity can have an ergoregion, in which all trajectories are dragged in the direction of the star's rotation. The existence of the ergoregion leads to a classical instability to emission of scalar, electromagnetic and gravitational radiation from the star. In this paper we calculate eigenfrequencies (including e-folding times) for stable and unstable modes of a scalar field on a background metric which has an ergoregion. Within a W.K.B.J. approximation for modes with angular dependence $\exp(im\phi)$, we find that unstable modes exist for all $|m| > m_0$ (m_0 depending upon the star), but that the e-folding time is asymptotically $\tau = \tau_0 \exp(2\beta m)$, where β is of order 1. Typically, τ_0 is several orders of magnitude longer than the age of the universe. However, the techniques evolved here should be applicable to other 'rotational dragging' instabilities in general relativity. Particularly useful should be the result that links the eigenfrequencies to resonances in the effective potentials governing photon motion in the metric; these potentials are rotationally 'split'.

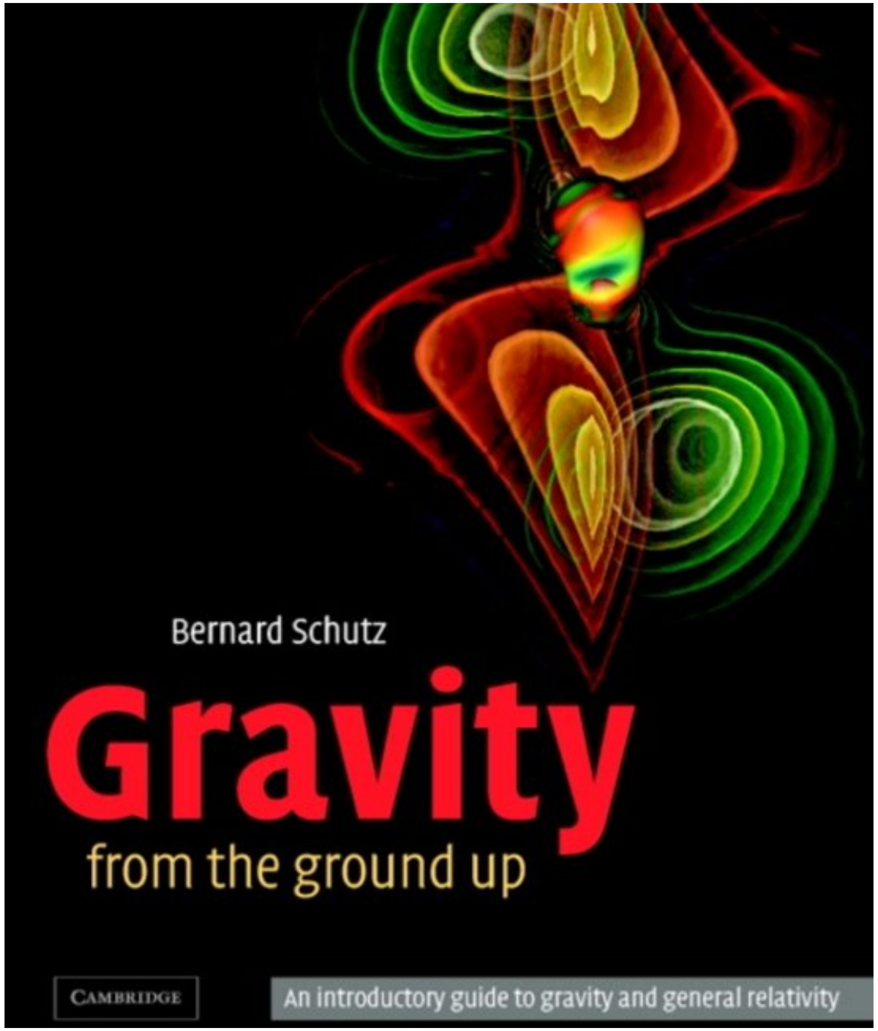
- There followed a lot of complex mathematics by Carter, Teukolsky, many others, guided by this physical picture.
- [And Hawking's radiation - a whole other story!!]
- In the mid-'70s, my graduate student Neil Comins and I looked at ergospheres of stars, with no horizon, and found them to be generically (but weakly) *unstable*.
- The prior understanding of the Penrose process and superradiance helped us see why our result was 'natural'.
- But it raised the question, why is Kerr stable? We only partially understand this even now.
- Neil is himself now a populariser of relativity and gravity.

Textbook writing

- FCGR was designed as a step toward the MTW 'bible' for my Cardiff students, who did not have previous exposure to relativistic EM or to variational principles.
- 'Math first' because MTW was.
- I felt it was important to explain concepts by building on existing ones, developing intuition, both for the physics and for the mathematical tools.
- 'Physics first' books, like Hartle, explicitly build intuition and let the mathematics bolster it.
- In all textbooks, exercises giving simplified applications of the theory can help build intuition.



Teaching from analogies and models



- After FCGR came out I spent 20 years trying to remove the calculus, to find ways not just to teach gravity, but to understand it in a natural way, an intuitive way.
- I learned a *huge* amount about GR by writing the book, by forcing myself to make clear connections that were only fuzzy to start with.

Gravitomagnetism and dark energy

- An example of what I learned and tried to convey was how to derive frame-dragging from a Lorentz transformation of basic Newtonian-like gravity.

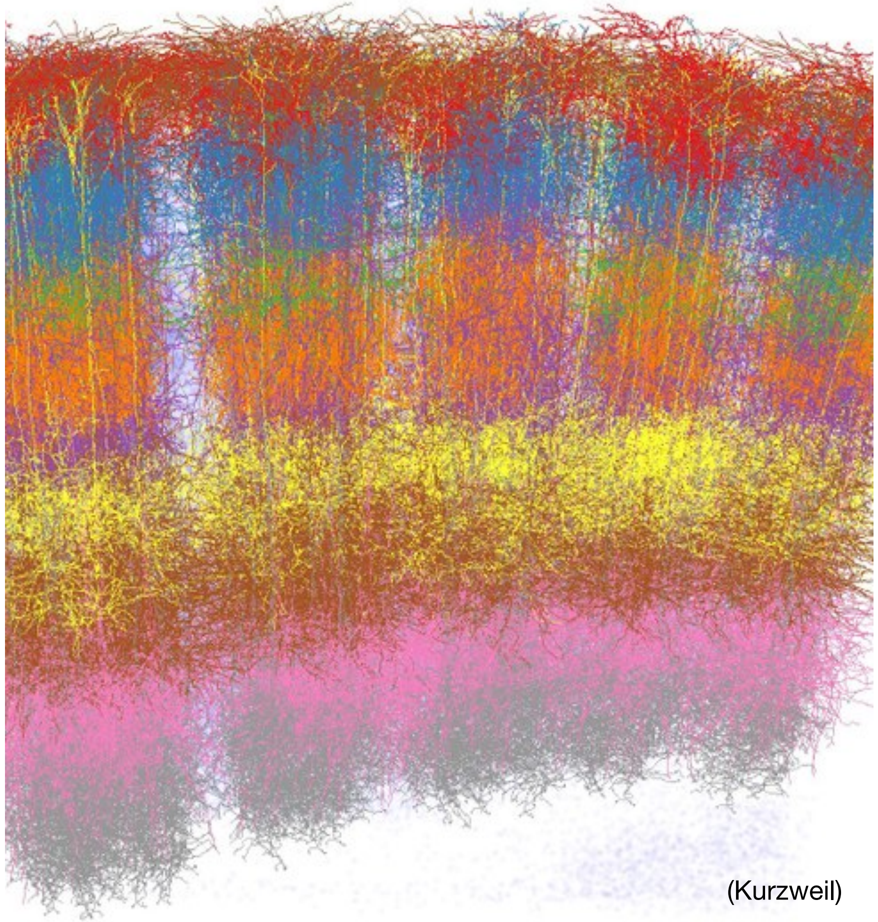
- I followed Feynman's derivation of magnetism from the Coulomb force using the Lorentz transformation of a system where a charge sits next to a wire carrying a current. This is a classic example of developing intuition in volume 2 of the Feynman lectures.

- Feynman uses but does not explicitly invoke the Lorentz invariance of the charge *e*. To make the analogous argument in gravity and get the GR result, you have to let mass-energy transform, *plus* you have to identify the source of the Newtonian-like part of the force as $\rho + 3\langle p \rangle$, or equivalently $T^{00} + T^i{}_i$.

- Having got this far, then it is now possible to understand how dark energy, the cosmological constant, accelerates the Universe by using the same $\rho + 3\langle p \rangle$. This unexpected link within GR is, to me, beautiful for being so unexpected.

Our brains: logical?

- Theoretical physics prides itself on its logic, but intuition is fuzzy and creative, not linear. To understand why we need both, look at the brain.
- A popular idea today in psychology about how brains work is that they are quasi-Bayesian.
- Brains take in current environmental information (evidence) and combine it with remembered experience (priors) to arrive at the 'best' decision.
- In people this seems like a good model of our unconscious mind, which elevates the 'best' thoughts up to our consciousness.
- So logic has nothing to do with this level of thinking; it is all statistics.
- Neural network computer systems deliberately imitate this way of making decisions.



(Kurzweil)

The importance of our unconscious decisions

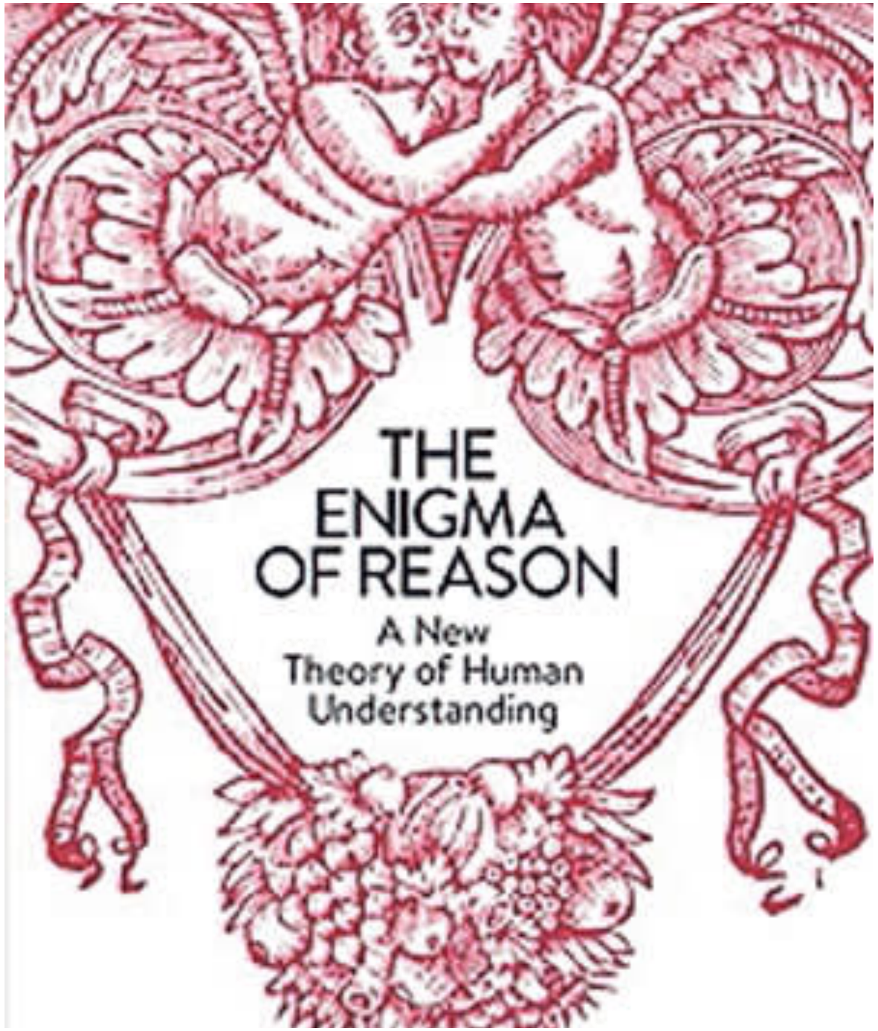
- Gerd Gigerenzer (MPI Bildungsforschung) is a well-known proponent of the idea that one should trust the result of all this percolation and winnowing going on in the cortex.
- His book *Gut Feelings: The Intelligence of the Unconscious* is a popular account of his ideas.
- But where do reason and analysis come into the brain?

Reasons are for others

- Many psychologists seem to think that reasoning is almost the same as rationalising: we use it to justify what comes up from the "gut".

- A recent book, *The Enigma of Reason*, by Mercier and Sperber, puts a different shading on this: our reasons are what we use to convince other people of our gut feelings, and we listen to their reasons in order to modify our own priors if necessary.

- This is a social, transactional view of reasons. They function in argument, dispute, the search for consensus. They are the way we communicate and evaluate our gut feelings.



What about physics?

- In all this there seems to be little room for Aristotelian logic or mathematical deduction.
- When we teach physics mathematically, we work within a theory and use logic to elaborate its ramifications. This can be analysis or, in modern times, computer simulations. Computer simulations are models that sometimes function like experiments, sometimes like proofs.
- Our proofs, derivations, and computer simulations become exceptionally strong *reasons*. If they coincide with experience, and/or mesh with other theories, they can become internalised into our priors.
- Our intuition, I would argue, works at the gut level. It generates hypothetical answers to new problems. These answers must then be tested by reasoning, possibly mathematically. Physicists are expected to do these tests themselves first, then bring them to others to argue about. If arguments can't be resolved then new experiments may do so.

Psychology		Physics
Gut level	$\Longmapsto$	Intuition
Reasoning	$\Longmapsto$	Mathematics

Training physicists

- Psychologists tell us that both levels are vital for humans: the gut feelings guide simple decisions and provide creative new ideas, while reasoning allows us to shape and to benefit from others' gut feelings. So a good physicist is one who has good intuition and good mathematical skills.

- This suggests that physicists should pay appropriate attention to both mathematical skills and physical intuition. Intuition should be cultivated, deliberately developed. New concepts should be presented both mathematically and with attention to "meaning", to links with other known concepts.

- Our intuition can be thought of as a model, an abstraction from the mathematical theory. Physicists with good intuition have mental models that are useful. But, like neural networks, they do not in any sense "represent" the real world. They are algorithms for reacting to the real world.

- To teach intuition, one may well find that physical or simplified mathematical models are useful. In this view, models in teaching are not just a way to help people "understand" a theory whose mathematics is beyond them. They can and should be used to help even mathematically literate students to develop their intuition.

- Maybe for GR textbooks we should not just talk about physics first or mathematics first. Maybe we need a scale 1-10 for how they develop physical intuition. And we should teach from the 10s!

What about high-school?

- Building intuition should start at school. But the goals are wider: students have to be captured, excited.

- Models become part of the argument for GR, part of the exchange of reasons that persuade students. Only after they open up does their intuition develop.

- For school students it is imperative to build a variety of models: physical, conceptual, and mathematical (with simple mathematics).

- The question will always be, when does simple become too simple? Does it assist, or mislead?

What is a good model?

1. Thought-provoking: Does the model challenge the priors, does it develop intuition? Does it illustrate key experiments or observations?

2. Extendable: Does the model lead anywhere? Can one build on it? Explain more than one thing? Or does it miss something important?

3. Open: Does the model encourage discussion, questioning? Students should understand that science is self-critical: does the model help with this?

In the end, we want students to find science interesting, but also to respect it. We want them to come away understanding how it deals with reality, how it makes progress. In a world full of fake news and reality-deniers, students need to understand that reality is not relative!