Arrows of Time

HW6 is due today (April 10)

Term paper draft next week April 17

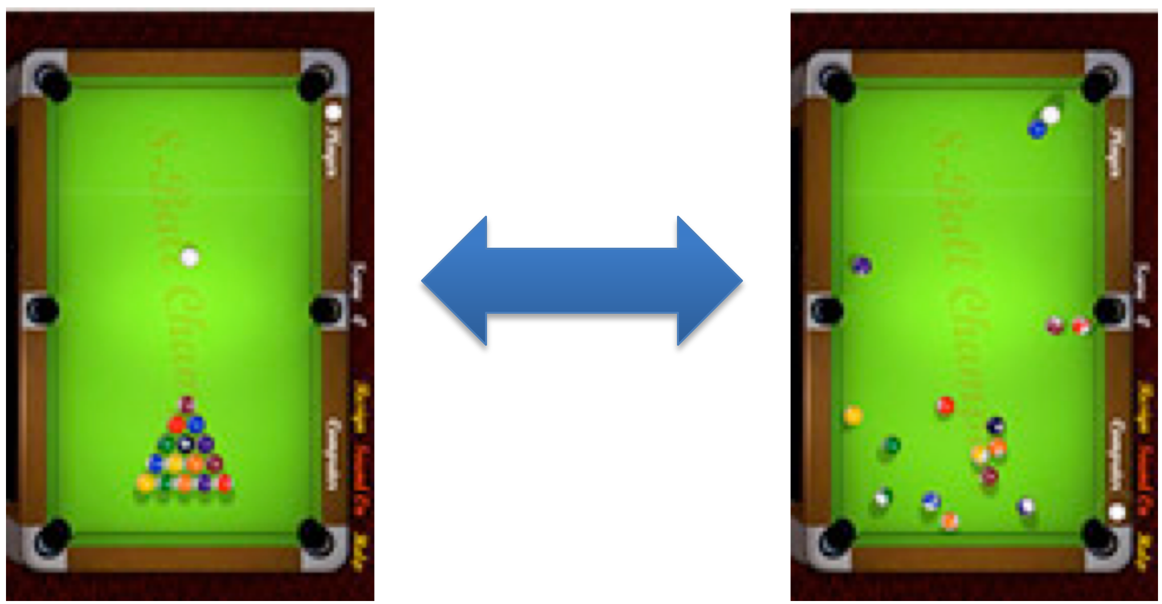
Main Arrows of Time

- **Psychology**: we remember the past, but we calculate the future.
- **Entropy**: always increases (2nd Law)
- **Quantum measurement**: the ambiguity in practice always concerns future states, not past ones.
- **Cosmology**: the universe is expanding, maybe forever.
- **Black holes**: the reversed object, a white hole, has never been found.
- **Radiation**: the E-M radiation field is determined by the sources it comes from, not the places it's going to.
- **The weak nuclear force** is not reversible.

Which occurs first?

How can you prepare the state?

Entropy?



Entropy and QM

- QM gets rid of some ambiguity about the meaning of entropy. Classically, entropy had something to do with the number of micro-arrangements consistent with the macroscopic appearance. This is ambiguous in several respects- one being that there is no obvious classical way of counting arrangements, which have a continuum infinity of possibilities. QM avoids this, because we can write a discrete list of quantum states and their probabilities, given some macroscopic knowledge of the system. Entropy is the log of the number of possible quantum states.
  - Technical details: some quantum states will in general be more likely than others, given known facts about the system. There's still a precise formula for the entropy in terms of the states' probabilities.
  - Sometimes what's known about the system says not just how likely it is to be in the various states in your list, but also what particular superpositions of those states are most likely. (e.g. two-well system, in one well) There's a precise generalization of the entropy formula which deals with those cases too: $-\mathrm{Tr}(\boldsymbol{\rho}\ln(\boldsymbol{\rho}))$.
  - The entropy comes out *independent of what list of quantum states you chose*.
    - e.g. eigenstates of energy, or eigenstates of some other variable

Entropy and Subjectivity

QM has also allowed us to clean up the definition of entropy
but the definition of entropy still has a somewhat subjective ring

- **If you specify the quantum state, the entropy is zero, because log[1]=0**
- Therefore the entropy is still a function of the set of variables specified (energy, etc.) and of the accuracy of their specification, not just of the state of the system.

Restate the second law

Left to itself, any nearly closed system is equally likely to end up in any of the allowed quantum states consistent with the known energy, number of particles, etc.

- **Therefore you will find the system with values of various measurable quantities which give maximum entropy,**
  - **i.e. are consistent with the maximum possible number of states.**
- **This remains highly directional in time. It says what will be, but not what used to be.**

Boltzmann's statistical argument for the 2nd law

1. **You don't know the actual microstate.**
2. **So your best guess about the future will be one consistent with as many microstates as possible, so long as they are consistent with the current observation.**
3. **Which can be shown to lead to constant or increasing entropy.**

What's wrong with that reasoning as an explanation for the time asymmetry?

Assume that Boltzmann's mathematical argument for point (3) is ok.

Boltzmann in reverse

Pointed out by Boltzmann's friend Loschmidt

1. You don't know the actual microstate.
2. So your best guess about the past will be one consistent with as many microstates as possible, so long as they are consistent with the current observation.
3. Which can be shown to lead to constant or *decreasing* entropy.
   By just the same math as used before.

A false conclusion!

- So Boltzmann must have snuck in an assumption:
  - essentially that the past was ordered in a special way which precludes the use of simple statistical arguments about it.
  - But that is precisely the asymmetry which we wanted to explain.
  - It's now clarified, but not at all explained.

Entropy: the Liouville problem

- There's a classical theorem that the volume in classical "phase space" that some system might be in *does not change in time* as it follows the classical equations of motion. But the classical entropy is just the log of the accessible volume in phase space.
- So how can it increase in time?

- Although the net volume in phase pace doesn't change, the possible results change from being a solid trunk of nearby values (all positions and momenta approximately known) to a set of small fibers (all the positions and momenta might be very near any of a large number of very different possibilities).
- If your description is forced to be "coarse grained" that means that you lose all predictability about the results. I.e. you get some useless information about exactly what the coordinates are if they are approximately known, but you lose the basic information about what the approximate values will be.
- How can a basic law of nature depend on our "coarse graining" of the description?

Why does S increase, not decrease?

- Boltzmann also argues that it is meaningless to argue about why the past is the low-entropy direction in time, that given an asymmetry we are bound to use different names for that direction and the other one.
- The question for Boltzmann is *why there's an asymmetry*, not why the "past" has a particular property.
- The implication is that if somehow a low-entropy configuration happened by very rare accident, the times around that, in which entropy is changing monotonically in time, will be suitable for experiencing one direction as past and the other as future.
- The explanation for why we are observing one of these rare stretches of time would then be that no observers could evolve in more ordinary, equilibrium times.
  - An early anthropic argument!
- This still does nothing to explain the *homogeneity* of time's entropic arrow: why would it be changing the same way throughout the known universe? If the original low-entropy condition is an accident, we need an explanation for why the whole universe is part of the same accident. That will require another look at cosmology.

Psychological impressions of times arrow

- **Intuitive**: time moves forward
- **Knowledge of past and future**: we remember the past we guess the future
- **Existence:** things in the past are objective; things in the future do not yet exist. How does relativity change this?
- **Possibility**: the past is unchangeable, one has a choice about the future (free will)
- **Causation**: the past conditions influence the future not the other way around.
- **Concern**: Our death concerns us, not our birth.

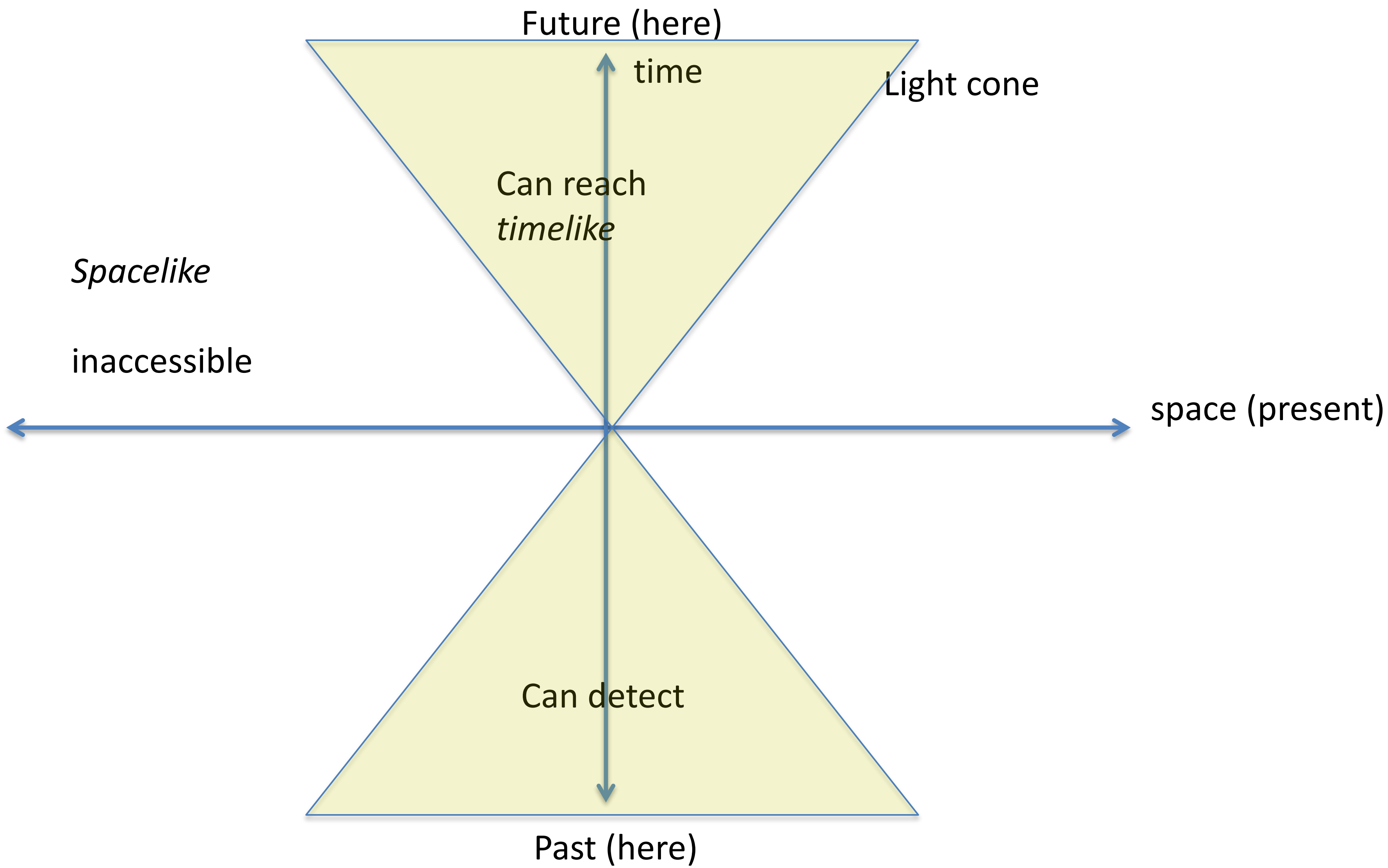
Relativity says there exists 3 categories of events relative to us (here and now):

- The past timelike
- The future timelike
- The present: spacelike

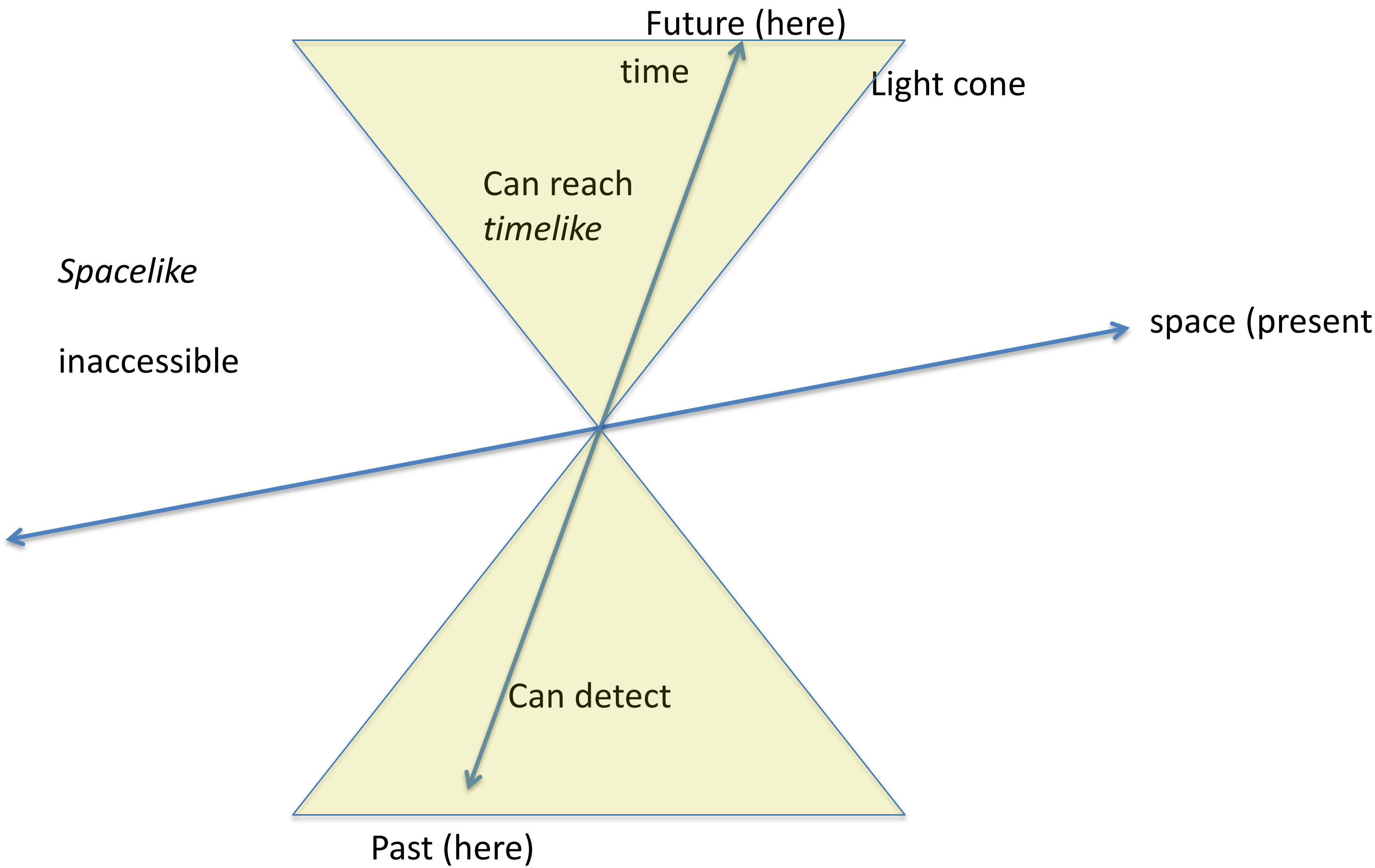
Other observers will disagree.

Einstein: *All of space-time is already determined. There is no uncertain future. The flow of time is just psychological*.

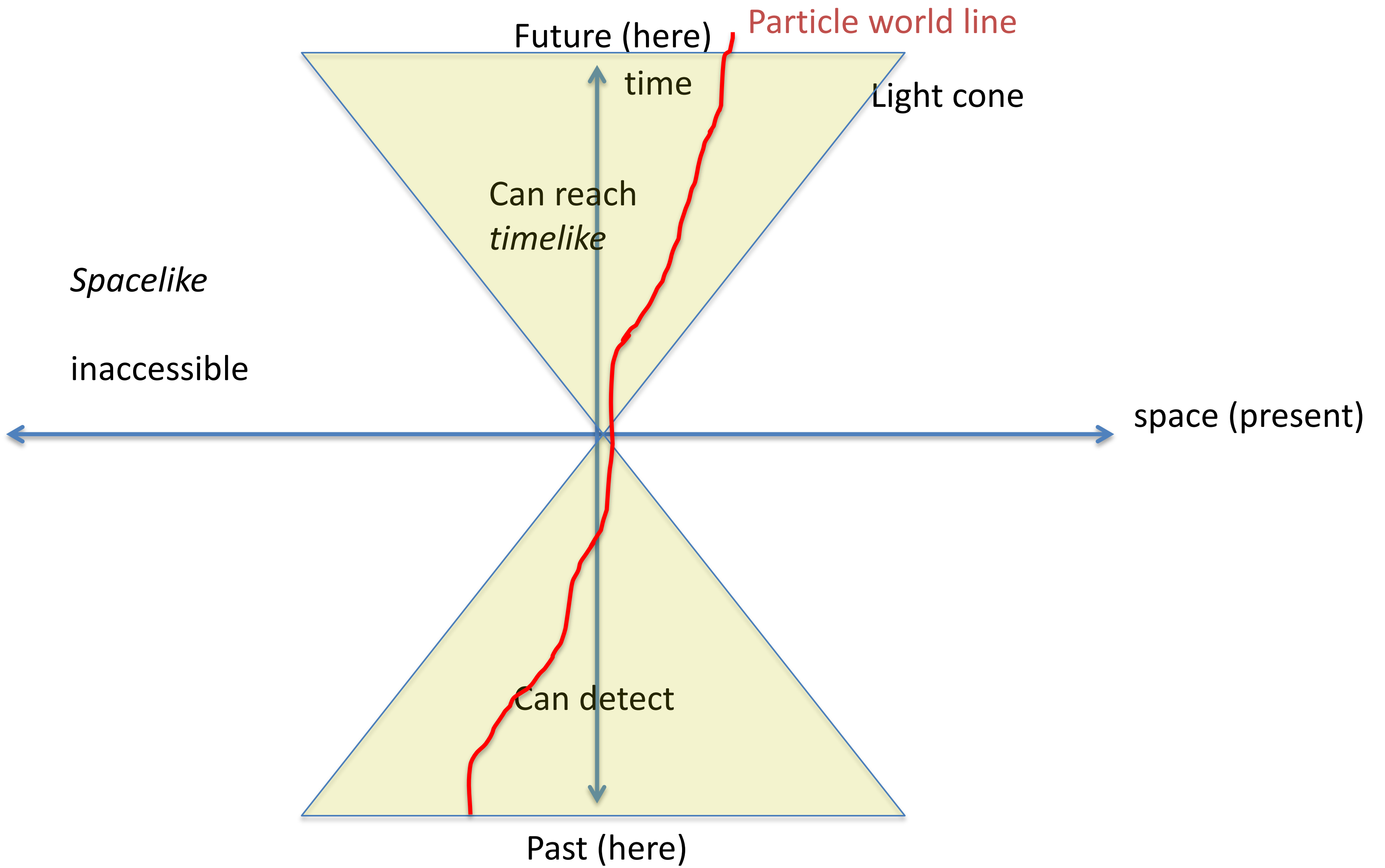
Space-time diagrams



Spacetime from rocket



Space-time diagrams



Psychology and entropy

(see Sklar, Hawking)

- There is a close connection between our mental asymmetry and the entropic asymmetry. For starters, in an equilibrated world (entropy already maximized, no entropic time asymmetry) there is no information (that's why Maxwell's demon can't function) so there could be no minds whatever.
- The low-entropy property of the past is needed to allow some information about it to be conveyed with a relatively small number of bits. a photograph of some place tells you a lot about it, but a photograph of some equilibrated mush conveys essentially no information. When we find some highly ordered artifact, (say a fossil) we use it primarily to find out about the *past*, not the future. The ability of the past to leave informative records reflects its order.
- Memories, like pictures, etc. are also an informative record of the past, stored in a small fraction of the number of particles represented. It is natural to informally associate the direction in time for which such mental records exist with the direction in time for which ordinary physical records exist. There is no formal proof that that direction is the same as the lower-entropy direction, since the near future is also very far from equilibrium and therefore in principle could also leave traces. Still, if you accept that the asymmetry between evidence of past and future states flows from their entropic asymmetry, there is no reason to exclude mental evidence. Probably the psychological arrow flows from the entropic arrow.

Electromagnetism?

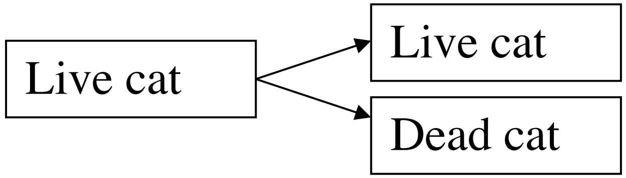
- Maxwell's Eqs. are time reversal invariant if we change B to –B.
- The radiation field in E-M is given as a function of the past positions, velocities, accelerations of charged particles. There is no reason in the formalism not to include future sources as well. Why the asymmetry?
- Actually, a given radiation field *can* be described either way, in terms of where it's coming from *or* in terms of where it's going to. It's a *convention* to always use the past sources not the future ones. This convention is strongly motivated by the *other time asymmetries*, specifically the entropic one.
- In an equilibrium condition, with particles emitting and absorbing radiation thermally, there would be no reason to pick the past over the future as the "source" of the radiation.
- We can dump radiation into the environment. "boundary conditions"
- So the radiation arrow is really another example of the entropic and (quantum measurement?) arrow.

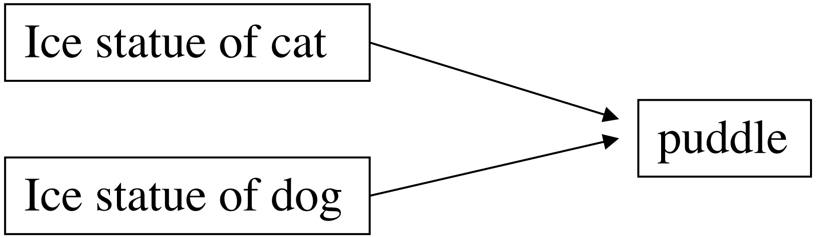
Psychology and quantum measurement.

- Let's imagine a world in which reversed QM measurements occurred. The current physical state of every object, including our brains, would be a potential outcome of the evolution of any of a number of macroscopically distinct prior states, just as in our world it could evolve into any one of a number of macroscopically distinct subsequent states.
- It would no more be possible to simply remember a unique past than it is now possible to accurately foresee a unique future in QM experiments (or anything else). In other words it would be impossible *in principle* to tell if a time-reversed cat had been alive or dead previously! Both memories would be equally valid.
- Philosophers would debate whether there really had been multiple distinct pasts, or if there were anti-collapses, in which the wave function acquired properties which looked just like those that would have been inherited from non-existent pasts.
- So the psychological distinction between past and future is very similar to the asymmetry of the QM measurement process.
- It is unclear if, without some coherent memory, any mind could develop to the point of wondering about symmetries. I.e. the QM measurement asymmetry may be a prerequisite for consciousness.

Entropy and Quantum Measurement

- Actual QM measurements often allow one macroscopic world to evolve into any of several possible distinct outcomes.
- The reverse process is not observed.
- Statistical mechanics describes events in which a large number of distinct possibilities evolve into results which are so macroscopically similar as to be practically indistinguishable.

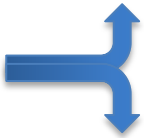




The result is that our world is consistent with only one past but many futures *in precise detail* (QM irreversibility) but macroscopic events are often consistent with a huge variety of *macroscopically* distinct predecessors, while often giving macroscopically unique consequences. This combined situation provides a possible arena for memory, i.e. detailed physical states which give information about the past which is not implicit in miscellaneous macroscopic events.

What about the "collapse of the wave function"?

- Its standard description sounds highly irreversible.
- Let's assume that the collapse actually happens. That means that a system which was in a single quantum state, which could turn out to have (say) two macroscopically distinct outcomes ends up in a state corresponding to only one of those. It's still in a single quantum state,
although not in one that could have been predicted ahead of time.

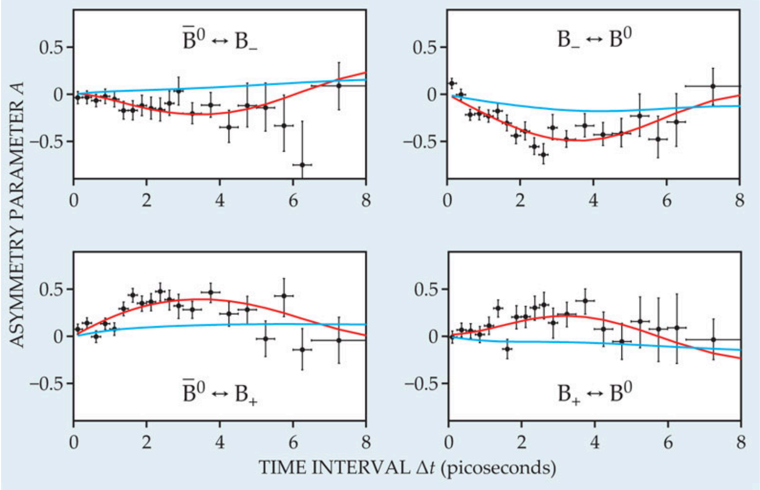


- In principle, the wave equation allows the following time-reversed situation: a system is found in a state which could have arisen from either of two macroscopically distinct predecessors. Then we could argue about whether both of those predecessors really existed (a reversed MW picture) or whether there had been a discontinuous change in a state to make it look just like one that could have arisen from another state (a time-reversed collapse picture).

- No time-reversed-measurement process has ever been observed.
- Thus QM also has an observed "arrow of time”.

The one known failure of microscopic time reversal

- Quantum field theory says that CPT (Charge-Parity-Time) symmetry is obeyed. This means if we film an antimatter world in a mirror, then show it backward, it will obey all the rules for a film of our own world running forward.
- In principle the *separate* symmetries (C, P, T) don't have to work.
- If time reversal invariance (T) holds, then processes should run equally well forward and backward.
- In elementary particle physics, there is a particle called the K^o meson. It has an antiparticle partner called the anti-K^o. the meson often decays: $K \rightarrow \pi\pi$.
  <u>The reverse process does not have the same rate</u>.
  - For practical reasons (other arrows of time!), this is not what is measured.
  - CPT is used to infer the reversed rate.
  - Other processes involving the weak nuclear force show T-violation directly.
- The one known microscopic asymmetry plays no role in ordinary events, but will be crucial to understanding the matter-antimatter asymmetry of the universe.



Cosmology and Black-Holes

- Various types of black holes (e.g. collapsed stars) follow naturally from the standard cosmological picture, together with the law of increasing entropy. There is no reason to expect there to be any white-holes (time-reversed black holes, with ordinary matter pouring out). However, they are also solutions of the G-R (reversible) equations. So there is presumably some connection between their absence and the other irreversibilities, but it is not yet elucidated.

Cosmology and entropy

- If the increasing-entropy arrow of time is to be consistent, there must be no backward-in time loops in space-time geometry. Any such loops would prevent there from being ANY consistent global time-ordering for the whole space-time, as we noted when worrying about causality.
- There have been many speculations that somehow the expansion of the universe and the increasing entropy are connected. Both at least affect all of the universe we know.
- Would a slowly contracting universe would obey different local laws than a slowly expanding one. If the universe were to someday start to contract, how would the behavior of steam-engines, change?
- Is irreversibility compatible with cyclic cosmologies?
  - In certain cases, it seems so.
    - Entropy associated with a given collection of matter goes up as it gets more entangled with other things.
    - Some re-start phenomena (collisions of infinite branes, birth of baby universes by quantum fluctuations) restarts some subset with low internal entropy/particle by increasing number of particles, not by entropy loss overall.

Links between between measurement and entropy arrows?

- Start with collection of little distinct non-interacting beads in an isolated container. Place them all in a small region. Each one's Ψ spreads out. Decoherence (via "measurement" entanglement with other things) would then split these spread-out Ψ's into different "worlds". After many repetitions of the process, the density of worlds (or potential worlds, if collapse happens) with any particle near any position would become uniform. If you haven't opened the box (i.e. let it interact enough with your mind to know the contents) the best guess you can make about its contents is based on that uniform probability density- the same one that the entropy maximization rule says to use.
- So the arrow that says the universe starts with low entanglement between remote objects is the same as the arrow that ordinary local entropy terms start small.
- If somehow the resolution of the measurement problem were to involve intrinsically non-linear irreversible violations of Schroedinger dynamics, that same fundamental irreversibility would also give the Second Law. That would get around the Loschmidt issue, of how to avoid the time-reversed version of Boltzmann's argument. The postulated hypothetical physical process would allow *only* probabilistic predictions, but would allow deterministic retrodictions.

Main Arrows of Time

- **Psychology**: we remember the past, but we calculate the future.
- **Entropy**: always increases (2nd Law)
- **Quantum measurement**: the ambiguity in practice always concerns future states, not past ones.
- **Black holes**: the reversed object, a white hole, has never been found.
- **Radiation**: the E-M radiation field is determined by the sources it comes from, not the places it's going to.
- **The weak nuclear force** is not reversible.

All of these arrows can be related to the cosmological arrow

- **Cosmology**: the universe is expanding, maybe forever.

Cosmological Arrow of Time

- The universe is expanding. Fewer states are available in a small universe
- Disorder never has a chance to catch up to the expansion.
- Our sun is a hotspot in a dark sky.
- Visible photons→infrared photons
- What would happen if the universe began contracting? Would time reverse?