Lecture 24 : *4+1 cosmic puzzles*

Four +one puzzles…

- The Flatness Problem.
- The Large-Scale Smoothness Problem.
- The Small-Scale Inhomogeneity Problem
- The Magnetic Monopole Problem.
- Origin of Baryons
- and some philosophy- fine tuning

"Ill tell you what's beyond the observable universe -- lots and lots of unobservable universe."

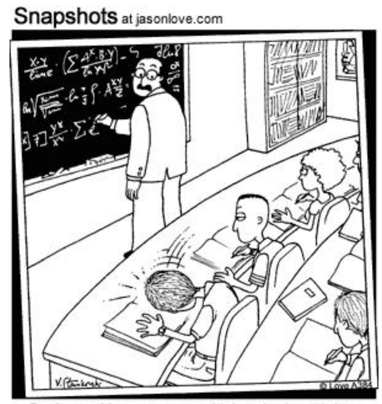
Reading: Chapter 16 of text (inflation)

- the CourseEvalUM website (www.CourseEvalUM.umd.edu) is open through December 14. The evaluations are confidential
- the summarized results are at the same location.
- the system does not identify to you whether or not they submitted an evaluation
- Please do this !- However I will not resort to bribery

"Instructor evaluation day!"

Difficulty of Material

- 'Cosmologists are often in error, but never in doubt.' Lev Landau
- these are VERY difficult concepts...please ask questions!



Professor Herman stopped when he heard that unmistakable thud -- another brain had imploded.

Some Philosophy

From 10^{-10} seconds to today the history of the universe is based on well understood and experimentally tested laws of particle physics, nuclear and atomic physics and gravity.
We thus have some confidence about the events shaping the universe during that time

Before 10^{-10} seconds, the energy of the universe exceeds the capabilities of the highest energy particle accelerators (~1 TeV before the LHC) and thus there is little direct experimental guidance (Cosmic rays have energies up to 10^{10} TeV). The physics of that era is therefore as speculative as it is fascinating.

The Big Bang has a singularity at t=0; things break down .. not physical?? or new physics??

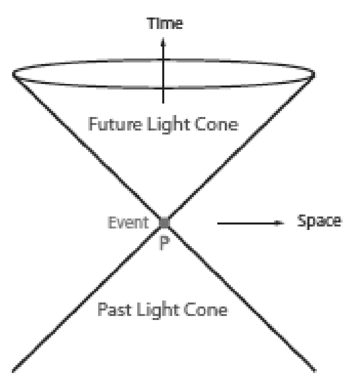
More Philosophy

Physicists want to understand things at the **most** fundamental level: (those nasty how, why questions; we have concentrated on the what, where and when)

Why is the universe isotropic and homogenous?
How do the ~20 free parameters of the standard quantum physics model occur? (mass of particles, strength of interactions)
How to reconcile General Relativity and quantum mechanics ? (quantum gravity)
What do the indications of physics beyond the standard model mean?

But we want solutions that are general- not fine tuned

- the conventional Big Bang model `begins' at a finite time in the past and at any time in the past the particle horizon was finite (~twice the Hubble length 8 Gpc), limiting the distance over which spacetime region could have been in causal contact.
- This feature is at the heart of the `big bang puzzles'.



Interior of cone is casually connected

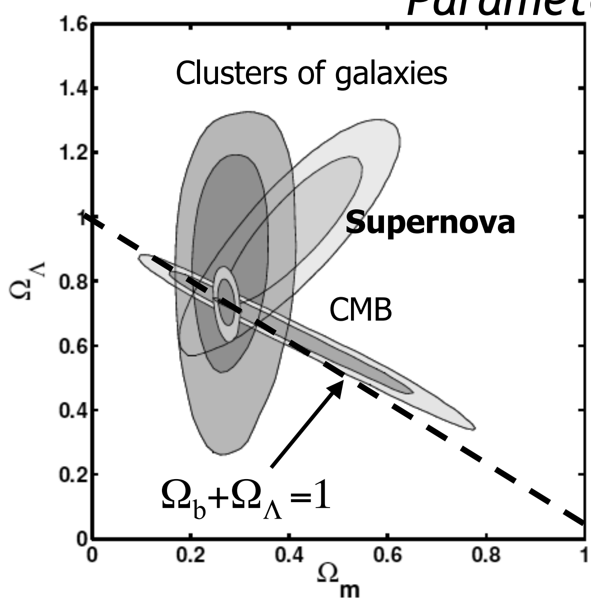
(see text pg 465-467)

I : THE FLATNESS PROBLEM

- Universe with a flat geometry is a very special case…
  - $\Omega = 1$ (for standard models)
  - $\Omega+\Lambda = 1$ (for models with cosmological constant)
- Our universe is almost flat…
  - We measure Ω_M approximately 0.3
  - CMB results suggest that $\Omega_M+\Omega_\Lambda \approx 1$ to within 1 percent or better!
- Why are we so close to this special case?

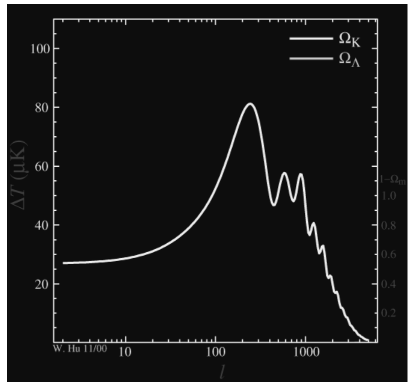
Best Present Constraints on Cosmological Parameters

- Data are perfectly consistent with a flat universe



CMB Measures Flatness

- The first peak in the power spectrum of the CMB is very sensitive to the flatness of the universe



It's worse than that: Ω changes with time

- $\Omega_{total} = \Omega_M + \Omega_\Lambda$
- eq 16.6 $\Omega_{total} = \rho/\rho_c = 1 + kc^2/H^2R^2$

  $|1-\Omega| = |k|c^2/[H(t)^2R(t)^2]$ {k=0,-1,1}

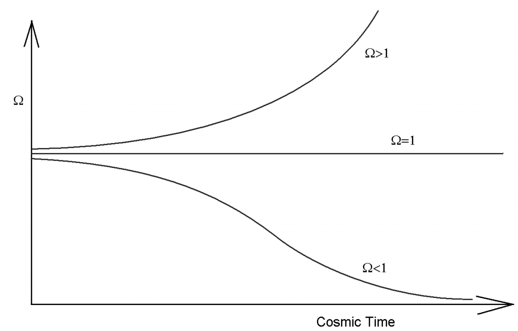
so as long as is $\Omega_{total} < 1$ it decreases with increasing time

- No matter what the cosmology Ω_{total} depends on time UNLESS $\Omega_{total} = 1$
- For a matter-dominated Einstein-de Sitter universe, $|1-\Omega| \sim t^{2/3}$
- For a radiation-dominated universe, $|1-\Omega| \sim t$

- <u>So, if Ω is close to 1 today, it had to be much much closer to 1 in the past!</u>

In fact, problem is much worse…

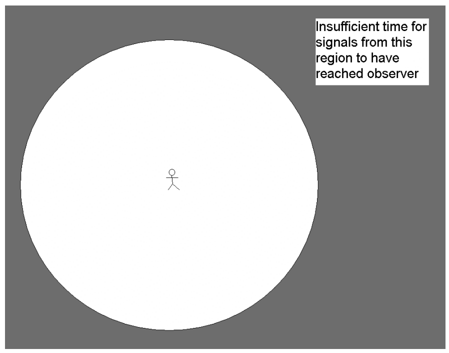
- If $\Omega \neq 1$, then value changes with cosmic time…
  - If $\Omega > 1$, then it grows larger and larger
  - If $\Omega < 1$, then it grows smaller and smaller
  - The closer Ω_{total} is to one the less it changes with time



- If the universe is approximately flat now, it had to be very, **very** flat at early times…
  - $\Omega \approx 1$ now means Ω (t = 1s) differed from 1 by less than 10^{-16} !!
  - At the Planck's time, Ω differed from 1 by less than 10^{-60} !!
  - So, very special conditions were needed in the early universe to give approximate flatness now.
  - If the Universe were not nearly flat, we would not be here…
    - If Ω had been much above 1, it would have recollapsed very early before making galaxies
    - If Ω had been much below 1, it would have expanded so rapidly that structures would not have formed
  - This requires a lot of fine tuning!
  - It is known as the **flatness problem**

II : THE HORIZON PROBLEM

- Concept of the particle horizon:
  - The sphere surrounding a given point (e.g., the Earth) which is causally connected to that point

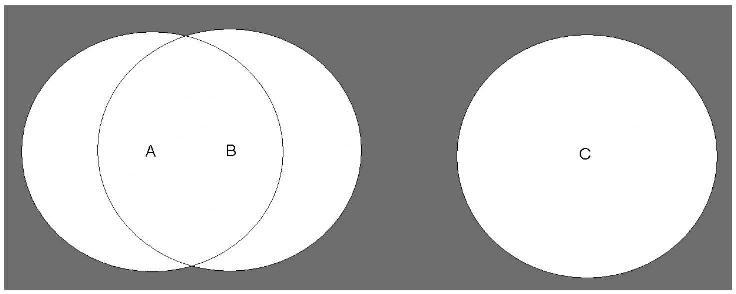


- The microwave background radiation from opposite directions in the sky is characterized by the same temperature to within 0.01%, but the regions of space from which they were emitted at 500,000 years after the big bang were more than the light transit time apart and could not have "communicated" with each other to establish the apparent thermal equilibrium - they were beyond each other's "horizon".
- Analogy:

If you have a big gas burner (the big bang), and put two saucepans with water on it, we expect the water in both pans to heat up and boil at ***almost, but not exactly*** the same time, because the flame is not exactly the same everywhere. There has to be "communication" or heat exchange between the two saucepans for them to heat up in exactly the same way. -

poor man's view of quantum fluctuations

- Consider 3 locations in space; A, B and C.
- Let's draw their particle horizons…



- So, in this example, A and B are causally connected to each other. But C is not causally connected to either A or B.

Size of the 'Observable' Universe

- The size of the lightcone ($r_{horizon}$) contains all of the universe that we can see or measure- *but this size changes with time.*
- $r_{horizon}$=2c/H= 8Gpc- but H=(dR/dt)/R
  for a flat universe $R(t)=R(0)(t/t_0)^{2/3}$ and thus

$H \sim 1/(t/t_0)$ - the size of the horizon is smaller at earlier times (exact values depend on k and Λ) .

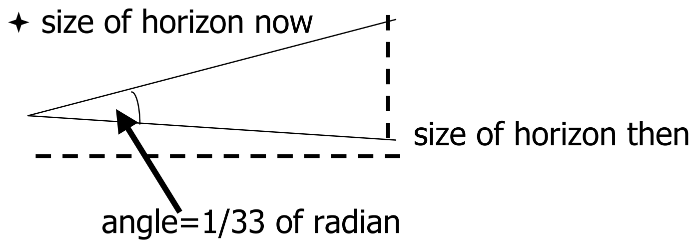
- Or (using eq 10.11- always true) $R_{now}/R_{then}=1+z$ and since recombination occurs at z=1100 ; R is only 8Mpc then
- Using a cosmologically correct calculation for a matter dominated universe the angle in the sky (today) for which blobs of the universe are connected at recombination (when the CMB formed) is $\theta \sim (\Omega_0/1+z_r)^{1/2} \sim 1.7\ \Omega_0^{1/2}$ degrees

Ω_0 is the present value of Ω

Where Does This Formula Come From?

- $R \sim t^{2/3}$ or $t \sim R^{3/2}$
- distance=(velocity)x(time) =dt/dR *c = c $R^{1/2}$
- size of horizon at recombination/size now= $(R_{recombo}/R_{now})^{1/2} = (1+z_R)^{-1/2}$

= $1100^{-1/2}$= 1/33 radian

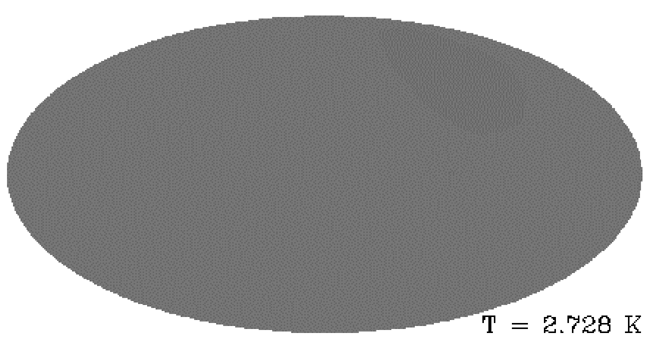


Size of the 'Observable' Universe

- But since the universe is 'only' 400,000 yrs old at this time, light can only go 0.1Mpc; so the universe is 'more disconnected- at this time objects that were further apart than 400,000 light years could not influence each other - now they are ~1000x further apart (400 million light years)
- How big is that in angular scale θ~size/distance ~400 million light years/angular distance ~1 degree

- Consider the "epoch of recombination"
  - Occurred ~400,000 yrs after big-bang
  - At that time, particle horizon would be roughly 10^6 light years across.
  - This size-scale at the redshift of decoupling (z = 1100) corresponds to an angle of about 1° on the sky…
- So, patches of the CBR that are separated by more than 1 degree should not have been in causal contact at the time of decoupling
- This gives the **horizon (or large scale smoothness) problem**

- There were a million causally-disconnected regions on sky at the time of last scattering
- How does the CBR "know" that it has to be so uniform across the sky?!



- The cosmic microwave background radiation is amazingly uniform- varying by 10^{-5}.
- Regions which are now separated by more than 1 degree are never in physical contact or communication if the universe is governed by a Friedmann-Robertson-Walker cosmology.
- Systems achieve thermal uniformity through conduction, convection or radiation transfer. All these require the constituents of the system to be causally connected.
- How could these different regions achieve identical temperatures to within one part in 100,000? This is the smoothness dilemma.

Say it again Sam

- The uniformity of cosmic background radiation--varying by < 1 part in 10,000, where ever you look--is a major problem for Standard Big Bang cosmology.
- At the time the universe began 14 billion years - look to the west, and measure the CMB: turn our radio antennas to the east, the CMB is at exactly the same temperature.
- The radiation from the east and the radiation from the west are separated by 28 billion light years.
- the radiation from the east could not possibly be causally connected to that from the west, because information cannot travel faster than the speed of light (the universe is too young). Nor could the regions they traveled from ever have been in communication.
- It's as if 200 students one in a huge introductory classes were taking a test and each student scores exactly 93% on the test. There had to be some cheating going on. But how?

- http://archive.ncsa.illinois.edu/Cyberia/Cosmos/HorizonProblem.html

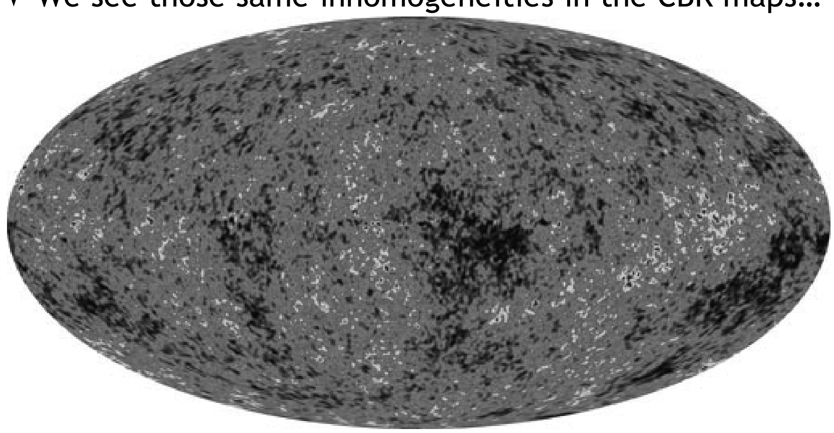
Say it again Sam

- The horizon problem gets worse if we travel back to the time when radiation was released from matter. The universe was 100,000 years old--the horizon was ~100,000 light years across. But the east and west photons reaching our radio antennae today were then separated by 10 million light years. That's 100 times the horizon!
- how can such two causally disconnected regions have one and same temperature?
- Isotropy was simply an initial condition specified by the Standard Big Bang model. But such ad hoc assumptions don't make for a very satisfying theory.

- http://archive.ncsa.illinois.edu/Cyberia/Cosmos/HorizonProblem.html

III : THE STRUCTURE PROBLEM

- Structure in the universe (galaxies, clusters of galaxies etc.) came from inhomogeneities in the early universe
- We see those same inhomogeneities in the CBR maps…



Structure Problem

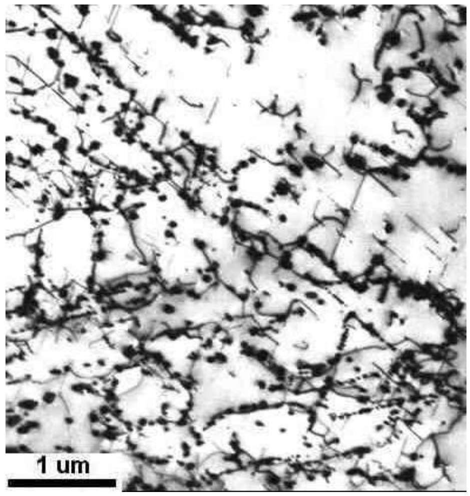
- How did those inhomogeneities get there?
- Why are they just the right magnitude, size and distribution in size to produce the structures we see today?
- How is it possible to have the same kind of inhomogeneities spread throughout the whole universe, despite the lack of causal contact between different parts of the early universe?
  - Galaxies, etc., that formed are similar in properties, on opposite sides of the Universe
- This is the **structure problem**.

- Partly similar in concept to the horizon problem- why are things so similar everywhere when they have never been in contact.

IV : THE RELIC PROBLEM

- Analogy: consider the cooling of a liquid (e.g., water)
- Once liquid reaches freezing point…
  - Freezing does **not** occur smoothly and uniformly
  - Freezing starts at certain locations, and the crystals start growing.
  - When crystals eventually merge to form the solid, there will be dislocations where the individual crystals meet…
  - The process of freezing is called a “phase transition” (matter changing from one phase to another).

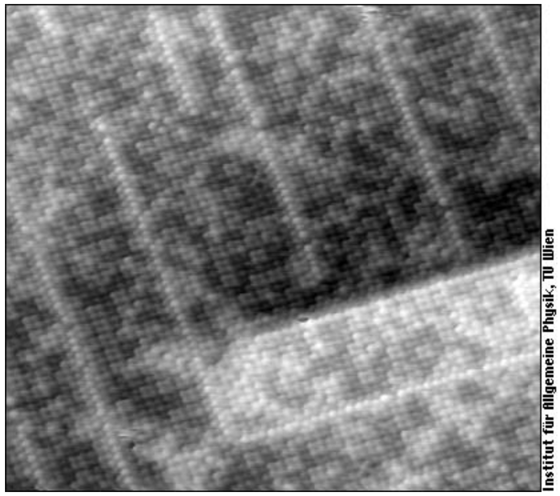
Dislocations in steel



Beer crystals (Bud)...

http://www.microscopy.fsu.edu/beershots/beerphotos.html

The atomic structure…



- What does this have to do with the Universe?
- "Quantum fields" related to particles and forces in the very early universe can undergo phase transitions (i.e., they "freeze out").
- As Universe cools…
  - The temperature falls to the point where certain phase transitions can occur
  - Phase transitions will start at particular points in space and grow at light speed
  - Can get "dislocations" produced in the universe as a result of different regions meeting

- This would produce exotic structure called topological defects…
  - Domain walls (2-d sheet-like structures)
  - Cosmic Strings (1-d string-like structures)
  - *None of these structures have been seen in the observable universe* (good limits from CBR data – strings would distort the background in a particular way)
- GUTs predict exotic particles (*Monopoles*) will be produced in the early Universe
  - Monopoles are predicted to be supermassive and carry magnetic charge.
  - why the universe isn't filled with them is one of the puzzles of the standard cosmology- about as abundant as gold but 10^{16} times more massive, so they "overclose" the universe. This catastrophe must be avoided! This was Alan Guth's initial motivation for inventing cosmic inflation.
  - Never yet detected… and they don't reveal their presence in any observed phenomena. Limits are very good. These objects have to be very very very rare.
- The absence of monopoles (and other relics predicted by particle physics theories) is called the **relic problem**

Where Do the Baryons Come From??

- If in the early universe equal amounts of matter and anti-matter are created one might expect either
  - 1) all annihilate and no matter is left
  - 2) there should be regions of matter and anti-matter in the universe

But:
no observable regions of anti-matter (having much anti-matter would foul up big band nucleosynthesis)
and
we have lots of baryons...

The challenges to the physics theories are then to explain how to produce this preference of matter over antimatter, and also the magnitude of this asymmetry.

This is all the more puzzling, because no laboratory experiment has ever observed baryon number to be violated, - in the laboratory it is always observed that the creation or destruction of a baryon is associated with the creation or destruction of an anti-baryon (haven;t reached high enough energies??)

Where Do Baryons Come from

- This is still an open issue ....
- There are numerous models of baryogenesis, many of which may be testable at the LHC ; to date, however, no single model has proven so successful that it has been accepted as a standard picture.
- The baryon asymmetry problem alone is evidence, from cosmology, of physics beyond the standard model of quantum mechanics.

- Limitations of the Big Bang Theory

The Big Bang theory successfully explains the "blackbody spectrum" of the cosmic microwave background radiation and the origin of the light elements, but it has several significant problems:

- The Flatness Problem:

CMB shows that the geometry of the universe is nearly flat. However, in Big Bang cosmology, curvature grows with time. A universe as flat as it is today requires extreme fine-tuning of conditions in the past, an major coincidence.

- The Horizon Problem/Structure Problem

Distant regions of space in opposite directions of the sky are so far apart that, assuming standard Big Bang expansion, they could never have been in causal contact with each other. This is because the light travel time between them exceeds the age of the universe. Yet the uniformity of the cosmic microwave background temperature indicates that these regions must have been in contact with each other in the past.

The fluctuations are the same everywhere in the universe

- The Monopole Problem:

Big Bang cosmology predicts that a very large number of heavy, stable "magnetic monopoles" should have been produced in the early universe. However, magnetic monopoles have never been observed, if they exist at all, they are much rarer than the Big Bang theory predicts.

✦Inflation Theory

- The Inflation Theory, developed by Guth, Linde, Steinhardt, and Albrecht, offers solutions to these problems and several other open questions in cosmology. It proposes a period of extremely rapid (exponential) expansion of the universe prior to the more gradual Big Bang expansion, during which time the energy density of the universe was dominated by a cosmological constant-type of vacuum energy that later decayed to produce the matter and radiation that fill the universe today.

- Inflation was rapid, and strong. It increased the linear size of the universe by more than 60 "e-folds", or a factor of ~10^{26} in only a small fraction of a second! it explains the above puzzles well, while retaining the basic paradigm of a homogeneous expanding universe. Moreover, Inflation Theory links important ideas in modern physics, such as symmetry breaking and phase transitions, to cosmology.

- The Flatness Problem:
- Imagine living on the surface of a soccer ball (a 2-dimensional world). It might be obvious to you that this surface was curved and that you were living in a closed universe. However, if that ball expanded to the size of the Earth, it would appear flat to you, even though it is still a sphere on larger scales. Now imagine increasing the size of that ball to astronomical scales. To you, it would appear to be flat as far as you could see, even though it might have been very curved to start with. Inflation stretches any initial curvature of the 3-dimensional universe to near flatness.
- The Horizon Problem:
- Since Inflation supposes a burst of exponential expansion in the early universe, it follows that distant regions were actually much closer together prior to Inflation than they would have been with only standard Big Bang expansion. Thus, such regions could have been in causal contact prior to Inflation and could have attained a uniform temperature.
- The Monopole Problem:
- Inflation allows for magnetic monopoles to exist as long as they were produced prior to the period of inflation. During inflation, the density of monopoles drops exponentially, so their abundance drops to undetectable levels.

- As a bonus, Inflation also explains the origin of structure in the universe. Prior to inflation, the portion of the universe we can observe today was microscopic, and quantum fluctuation in the density of matter on these microscopic scales expanded to astronomical scales during Inflation. Over the next several hundred million years, the higher density regions condensed into stars, galaxies, and clusters of galaxies.

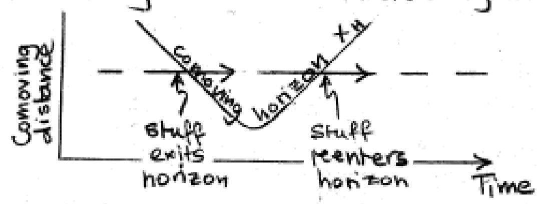
Are objects "coming in over the horizon" or "going out over the horizon"?

Have $x_H = \dfrac{c}{aH} = \dfrac{c}{\dot{a}}$, where $H = \dfrac{\dot{a}}{a}$

So

x_H is increasing if $\dot{a}$ is decreasing (decelerating)

" " decreasing " " " increasing (accelerating)



Stolen from Andrew Hamilton course notes at U of Colorado