Reader's Guide for ***Black Holes and Time Warps***

David Weinberg, 4/12/2025

These notes are to help A2142 students keep track of the key points in our fairly long book. I've written about chapters 3-13 for now, and may add more in the future.

Chapter 3: Black Holes Discovered and Rejected

pp. 122-123 describe the "Newtonian" calculation of a "dark star" whose gravity would be strong enough to trap light.

p. 124 introduces us to Karl Schwarzschild, the astrophysicist who discovered the first exact solution to Einstein's equations (known as the "Schwarzschild metric").

pp. 124-130 describe the Schwarzschild solution to Einstein's equations and introduce the idea of an embedding diagram (Fig. 3.3.) to represent curved space.

pp. 131-134 and Fig. 3.4 describe the black hole phenomenon from the point of view of GR and the Schwarzschild solution.

pp. 134-139 describe the resistance to the idea of a black hole, in particular Einstein's incorrect argument that an object dense enough to trap light could not exist (Fig. 5.3).

Chapter 4: The Mystery of the White Dwarfs

This chapter is largely the story of Subrahmanyan Chandrasekhar and his discovery of the maximum possible mass of white dwarf stars.

pp. 140-145 describe what white dwarf stars are (mass comparable to the sun but radius comparable to the earth) and how they are supported against gravity by electron degeneracy pressure.

pp. 146-149 describe the phenomenon of electron degeneracy pressure and its relation to the wave/particle duality of quantum mechanics (Box 4.1).

pp. 149-152 describe the startling discovery by the 19-year old Chandrasekhar, on his sea voyage from India to England, that a white dwarf's resistance to compression will become weaker if the velocities of its degenerate electrons approach the speed of light, and that there is therefore a maximum possible mass of white dwarf stars, about 1.4 times the mass of the sun.

pp. 153-163 describe Chandrasekhar's efforts to convince others of the correctness of his maximum mass finding, against the particularly fierce resistance of his mentor, Arthur Eddington. Eddington thought that there could not be such a maximum mass, because if there was then it suggested that more massive stars would keep contracting or collapsing until they formed black holes (a term that did not yet exist).

Chapter 5: Implosion is Compulsory

pp. 164-174 describe the discovery of supernovae by Fritz Zwicky and Walter Baade and their adventurous, insightful, and accurate suggestions that (a) neutron stars exist, composed mainly of neutrons and with density comparable to that of an atomic nucleus, (b) a supernova explosion is powered by the release of gravitational energy when the core of a normal star collapses into a neutron star, and (c) cosmic rays are particles energized by supernova explosions.

pp. 175-178, and especially Fig 5.3, explains how the question of the maximum mass of neutron stars relates to the question of whether dying stars will produce black holes.

pp. 178-187 are a historical digression about the Soviet physicist Lev Landau and his proposal of neutron stars. It's a great story, though not critical to our larger theme except in a historical sense.

pp. 187-191 describe J. Robert Oppenheimer and his work with graduate students Robert Serber and George Volkoff and collaborator Richard Tolman on the structure of neutron stars, in particular the demonstration that there is a maximum mass of neutron stars analogous to the maximum mass of white dwarfs.

pp. 197-208 describe John Archibald Wheeler and his work on the "equation of state" (pressure vs. density) for what Thorne terms "cold, dead matter", which ultimately reinforces the conclusion (Fig. 5.5) that for sufficiently massive objects there is nothing that can support them against gravitational collapse forever.

pp. 206-207 are interesting musings by Thorne on the differences between Zwicky and Oppenheimer and their scientific impact.

The critical bottom line of this chapter is that neutron stars exist and form in supernovae, but they have a maximum mass and therefore cannot be the end state of sufficiently massive stars. Thus, a sufficiently massive star must implode once it no longer has a way to maintain heat and high pressure at its core — implosion is compulsory.

Chapter 6: Implosion to What?

pp. 209-219 describe the calculations by Oppenheimer and his student Hartland Snyder of what happens during gravitational collapse, the first glimpse of black hole formation. pp. 217-219, in particular, zero in on the difference of appearance of the phenomenon from a reference frame far from the collapsing star and a reference frame moving with the collapsing surface.

pp. 219-235, the "nuclear interlude," describe the efforts by American and Soviet scientists to build first the fission bombs used in World War II and then the more powerful hydrogen bombs powered by nuclear fusion. If you are interested in learning more of this remarkable story, I recommend the superb book *The Making of the Atomic Bomb*, by Richard Rhodes. These pages also introduce us to the brilliant Soviet physicist Yakov Zeldovich, who plays important roles in what is to come.

pp. 235-243 describe the first calculations of stellar implosion that include detailed physics of the collapsing material in addition to gravity, which built on the lessons learned and computational tools developed in the atomic bomb and hydrogen bomb projects. Thorne's vignette about X-ray pressure and the hydrogen bomb (pp. 242-243) is pretty remarkable.

pp. 244-254 are the most important part of this chapter from our point of view, describing how the coordinate system developed by David Finkelstein allowed a holistic description of stellar collapse to a black hole, explaining why the collapse seems to "freeze" when observed from a large distance. Figures 6.6 and 6.7 and the associated description in the text are especially useful. Figure 6.8 shows how the "dark star" imagined in Newtonian gravity differs from the black hole described by GR.

pp. 254-257 describes how the names that we give to phenomena can influence the way that we think about them, and it explains how "black hole" came to be the standard term for a gravitationally collapsed object that traps light.

Chapter 7: The Golden Age

This chapter is optional reading. It is a terrific account of the development of the theory of black holes, as seen by one of the participants, including fascinating discussions of the nature of mentorship and the difference between the American, British, and Soviet academic systems.

pp. 258-272 focus on the "mentors" who taught a generation of black hole researchers, especially John Wheeler, Yakov Zeldovich, and Dennis Sciama, and they describe Thorne's own introduction to BH research as a student of Wheeler's.

pp. 272-286 describe the discovery of the important mathematical theorem known as "black holes have no hair." This theorem shows that the spacetime around an isolated, static black hole depends only on the black hole's mass, electric charge, and spin.

pp. 286-295 are the ones that we may come back to read later. They describe the theoretical discoveries about black hole spin and its impact on spacetime, which plays an important role in understanding some observed phenomena of black holes.

pp. 295-299 describe the more esoteric subject of black hole pulsations — though this subject is becoming relevant again because of the measurements of gravitational waves.

Chapter 8: The Search

This chapter describes the search for and discovery of stellar mass black holes.

pp. 300-309 explain why directly detecting black holes is difficult and explain the idea developed by Zeldovich and Novikov for how to find them as X-ray sources in binary star systems.

pp. 309-318 describe the development of X-ray astronomy, including the initially surprising discovery that there are many luminous X-ray objects in the sky. Many of these turn out to be binary systems in which gas from a "normal" star is being pulled onto either a neutron star or a black hole. This section also explains how one uses observations of the "normal" star's motion to try to determine whether the compact object is massive enough that it has to be a black hole.

pp. 319-321 explain the mix of scientific expertise that was required to enable the observational discovery of black holes.

Chapter 9: Serendipity

This chapter describes the discovery of supermassive black holes. In contrast to stellar mass black holes, these objects were not predicted by theory, so their discovery was not a consequence of systematic search but a serendipitous (lucky) consequence of advances in observational techniques.

pp. 322-330 describe the early days of radio astronomy, starting with the first radio observations of the sky by Karl Jansky and, later, Grote Reber. Figure 9.1(d) shows Reber's early map of the radio sky; Cygnus A, the bright radio source in the constellation Cygnus, turned out to be the first discovered radio galaxy. This section describes the challenge of getting good resolution with radio telescopes (because the wavelengths radio waves are long) and the idea of using networks of telescopes, interferometers, to achieve higher resolution.

pp. 330-334 describe early observations of radio galaxies, in particular the demonstration that much of the radio emission comes from lobes that are hundreds of thousands of light years from the central galaxy.

pp. 334-338 describe the startling discovery that some radio sources were associated with quasi-stellar objects (points of light on the sky) with large redshifts implying that they are very far away and must therefore be enormously luminous. Variability further showed that the emitting regions must be very small, a light-month in size or less.

pp. 338-342 describe the origin of radio emission and the energetics of quasars, leading to the conclusion that they are probably powered by gravitational accretion onto supermassive black holes.

pp. 342-346 describe further advances in understanding radio galaxies as powered by jets from a central black hole, and advances in radio interferometers producing much higher resolution images of radio galaxies (e.g., Figure 9.5).

pp. 346-354 describe ideas for how black holes might produce jets, and more generally how they can produce the phenomena we observe in quasars and radio galaxies. You don't need to understand in detail the four ideas illustrated in Figure 9.7; Thorne is especially enamored of the fourth of these because it is such an elegant idea, but I agree with Thorne's conclusion (p. 351) that "all four methods ... probably operate, to varying degrees ...".

pp. 354-356 discuss the relation between supermassive black holes and galaxies. We know a lot more about this now than we did in 1993. Consistent with Thorne's speculation, we know that most big galaxies harbor a supermassive black hole at the center, including the Milky Way, which has a (relatively modest) 4 million solar mass black hole. Most of the time these black holes are "dormant" – not being fed much gas, so not generating much EM radiation. However, when a lot of gas does get dumped on them, they light up as quasars or as less luminous (but still bright) "active galactic nuclei."

Chapter 10: Ripples of Curvature

This chapter tells the story of gravitational waves and efforts to detect them. It is fascinating to read the account now, knowing how the field has developed.

pp. 357-365 provide a great theoretical description of gravitational waves produced by merging black holes, a description that still reads as accurate 30+ years later.

pp. 365-378 describe the efforts to find gravitational waves with bar detectors, which would "ring" at a resonant frequency when perturbed by passing waves. The material on quantum non-demolition (pp. 372-377, Box 10.2 and Fig. 10.3) is interesting but technical, and not crucial to understand. The comment on p. 378 about why bar detectors would ultimately be limited even if they succeeded is important.

pp. 378-393 describe the idea of interferometric gravitational wave detectors and the origin of the LIGO project. Particularly important for our purposes are the description of gravitational waves at the bottom of p. 379 and top of p. 380, and the description of how interferometers work in pp. 383-387, Fig. 10.6, and Box 10.5.

pp. 393-396 give Thorne's speculation on what gravitational wave astronomy might look like "in the early 2000s." His timeline proved highly optimistic: LIGO did not detect gravitational waves until 2015. However, these pages are a reasonably close approximation to what gravitational wave astronomy looks like today, though our detectors are not yet as powerful as the ones Thorne imagines here.

As Thorne notes on pp. 392-393, the first demonstration of the existence of gravitational waves was indirect, from their impact on the orbit of a binary neutron star, and that demonstration won the Nobel Prize for Russell Hulse and Joe Taylor in 1993.

The direct detection of gravitational waves by LIGO in 2015 is one of the truly great achievements of 21st-century physics thus far, and this chapter from 1993 gives you a sense of just how long a journey it took to get there. Kip Thorne, Rainer Weiss, and Barry Barish won the 2017 Nobel Prize for their leading roles in this achievement, though it took a collaboration of many hundreds of people to pull it off.

Thus far, what LIGO has seen is remarkably close to what one might have guessed it would see in 1993, such as pp. 357-365 of this chapter. It hasn't seen anything as bizarre as the second panel of Figure 10.9, which is possibly disappointing. Gravitational waves have dramatically confirmed our understanding of General Relativity and black holes, and they have revealed some surprises (e.g., a larger number of very massive black holes than one might have expected). However, in my assessment they have not yet realized Thorne's hope (p. 379) that "gravitational waves might revolutionize our understanding of the Universe even more than did radio waves and X-rays."

But gravitational wave astronomy is still a young field, so more revolutionary discoveries may come in the future.

Chapter 11: What is Reality?

We aren't reading chapter 11, and I won't provide much of a summary.

But in brief, this chapter explains that one can describe the same phenomena of black holes in ways that convey very different physical pictures, which Thorne describes as different paradigms (using a term first applied to scientific theories by the historian and philosopher of science Thomas Kuhn).

In the usual paradigm, the event horizon is just a boundary between regions that can and cannot communicate with the distant world.

This chapter focuses on the *membrane paradigm*, a way of formulating the General Relativity equations around black holes in which the event horizon seems to act like a physical membrane that electromagnetic fields can attach to.

Because they are based on the same underlying principles, the two paradigms should give the same predictions for anything one can measure. However, they give different intuition for what is happening "in reality," and for some kinds of predictions it may be easier to work with one paradigm than the other.

The duelling paradigms described in this chapter — each useful in some regimes — suggest that we should be cautious in interpreting a particular physical theory as a description of "reality" beyond its predictions for concretely measurable phenomena.

On the other hand, the fact that theories do make successful predictions for phenomena that have never previously been observed or perhaps even conceived (such as gravitational waves) tells us that successful theories are not just compact encapsulations of existing knowledge.

Chapter 12: Black Holes Evaporate

This chapter describes the startling theoretical discovery, based on what Thorne describes as a "partial marriage" of General Relativity and quantum mechanics, that black holes can radiate energy and lose mass, eventually evaporating.

It is important to know that, although physicists are generally convinced that this Hawking radiation is a real phenomenon, we have probably never observed it in actual black holes, and we probably never will.

pp. 411-417 describe the insight by the physicist Stephen Hawking that in any event involving black holes (mergers of black holes, stuff falling into black holes), the total area of event horizons must always increase, never decrease. To reach this conclusion, Hawking needed a different definition of an event horizon, known as the *absolute horizon* in contrast to the *apparent horizon* (explained in Boxes 12.1 and 12.2).

As described in pp. 417-419, the absolute horizon at first seems like an odd quantity to define because to calculate it one has to "know the future," but it has the important advantage that it changes continuously rather than discontinuously as a black hole forms and grows.

pp. 419-422 tell us more about Hawking and the impact of ALS on his life and his work. (This story is nicely told in, among other places, the 2014 film The Theory of Everything; the actor Eddie Redmayne won the Academy Award for his portrayal of Hawking.)

Thermodynamics, largely (though not entirely) developed in the 19th century, is the area of physics that describes energy, temperature, and pressure, especially as applied to large collections of atoms and molecules.

pp. 422-427 describe the concept of *entropy* from thermodynamics, with a nice example in Box 12.3. The second law of thermodynamics states that entropy always increases. Several physicists, including Hawking, noted that his area increase theorem for black holes made the area of event horizons seem analogous to entropy. Most of them did not take this idea very seriously, but graduate student Jacob Bekenstein did, and he did calculations suggesting that a black hole's event horizon area really could be taken as a measure of its entropy. Furthermore, Bekenstein, Hawking, and others showed that one could draw several analogies between black holes and thermodynamics — if one identified particular quantities between the two theories, then the equations describing them were identical.

A big source of skepticism about black hole thermodynamics is that it implied that a black hole's surface gravity (roughly $GM/R_{\rm Sch}^2$) should be interpreted as a temperature, and thermodynamics tells us that a body with a temperature hotter than its surroundings should radiate energy.

pp. 428-434 describe theoretical calculations by Yakov Zeldovich and others implying that spinning black holes should radiate, with the radiated energy causing the black hole's spin to slow down. These calculations were based on a combination of General Relativity and quantum mechanics, particularly the quantum phenomenon of vacuum fluctuations described in Box 12.4. Among other things, these pages (and the rest of the chapter) offer a remarkable example of Zeldovich's style of thinking and of interactions between American, European, and Soviet physicists in the 1970s.

pp. 435-439 describe Stephen Hawking's astonishing theoretical discovery, again based on quantum mechanics in the neighborhood of an event horizon, that even non-spinning black holes will radiate energy. This was harder to believe than the result for spinning black holes, because in this case the radiated energy has to come at the expense of the black hole's mass instead of its spin — the mass must decrease, and the event horizon shrink.

Mathematically this result doesn't contradict Hawking's area increase theorem because that was based on "classical" General Relativity with no quantum effects.

pp. 439-441 describe the most commonly used intuitive picture for understanding Hawking radiation (Figure 12.2): the tidal gravity near an event horizon pulls apart a pair of virtual particles, and one falls into the black hole while the other escapes. A key conclusion (from the full calculations as well as this intuitive picture) is that the Hawking radiation typically has a wavelength similar to the Schwarzschild radius.

pp. 441-446 describe an alternative way of thinking about Hawking radiation, from the reference frame of an accelerated observer hovering above the event horizon. The most important concept from these pages is the understanding of black hole entropy, that *A black hole's entropy is the logarithm of the number of ways that the hole could have been made* (p. 446).

pp. 446-448 describe the timescale of black hole evaporation. Although the possibility of evaporation through Hawking radiation is an important point of principle, the time for a stellar mass black hole to evaporate is much, much longer than the age of the universe. *If* phenomena in the early universe (when it was less than a second old) produced *primordial* black holes with a mass roughly that of a mountain, and a Schwarzschild radius about the size of an atom, they would be able to evaporate within the age of the universe.

We do occasionally see bursts of gamma rays or X-rays, and in principle some of those could be the death throes of evaporating black holes. However, there seem to be other, less exotic explanations for these bursts. This is the reason I say we have "probably" never observed Hawking radiation, rather than definitely.

13. Inside Black Holes

We're not reading this chapter, but I'll give a brief summary in case you decide to read it for your own interest.

This chapter describes Thorne's ideas, as of 1993, about what the structure of black holes might be like inside the event horizon. Most of the discussion is based on "classical" General Relativity, ignoring quantum mechanics, under the assumption that quantum mechanics will only matter very close to the central singularity. There is some speculation of how quantum mechanics might alter these expectations. Overall, this is a speculative chapter, since we have never observed anything about the interior of black holes!

pp. 449-453 describe the idea of a singularity, a point at the center of the black hole that has infinite density and produces infinitely strong tidal stretching as one approaches it. Oppenheimer and Snyder's calculations for a spherical imploding star imply that it should form such a singularity, and the effects are illustrated in Figure 13.1.

pp. 453-455 (and Figs 13.2, 13.3) describe calculations aimed at discovering whether small departures from spherical symmetry would prevent a singularity from forming.

pp. 456-459 (Figure 13.4) describes the exotic idea that instead of a singularity the curved spacetime inside a black hole might open out into another universe or a different location in our universe. The end of this section gives a nice summary of where the understanding of singularities stood in 1964.

pp. 461-472 introduce us to Roger Penrose (already encountered in Chapter 7) and his mathematical proof that black holes must contain singularities. However, Soviet physicists argued for a different conclusion before finally conceding the argument.

pp. 472-480 give what Thorne describes as his best guesses (as of 1993) about the interior of black holes. The key point is that the central singularity produces chaotically changing tidal forces, as predicted by the Soviet physicists, rather than the smoothly increasing tidal forces predicted for a spherical collapse. However, these would still destroy infalling objects before they reach the scale where we expect quantum gravity effects to be important. Thorne then speculates on what the impact of quantum gravity might be close to the singularity.

pp. 480-482 describe the "cosmic censorship conjecture," the hypothesis that any spacetime singularity must be shielded from distant view by an event horizon. There are mathematical arguments supporting this conjecture, but not a general proof, so we do not know if it is correct.

In the years since 1993, there have been many theoretical investigations of black hole interiors and quantum gravity. Many of these investigations are motivated by the so-called "information paradox": if a black hole forms, then evaporates by Hawking radiation, it seems as though information about what formed the black hole in the first place has vanished.

None of these ideas are fully compelling, but string theory is a possible unified way of treating gravity and quantum mechanics that allows some properties of black holes to be calculated.

Most notably, OSU's Samir Mathur and his collaborators have argued that the event horizon of a black hole encloses not a singularity but an extended distribution of strings, which he refers to as a "fuzzball." This radical idea is a conjecture, not proven, but it is taken seriously by many physicists working in this area.