The Gravitational Wave Analogy

In the early years of the twenty-first century, several large detectors designed to be the first “observatories” of gravitational waves went, one by one, into operation. These detectors trace their ancestry to around 1960, when Joseph Weber, an American physicist working at the University of Maryland, first began the experimental effort to detect gravitational waves. Until 1969 the “field” of gravitational wave detection consisted of Weber and his students, but when he claimed to have detected gravitational waves (Weber 1969), others (some of whom had previously considered working on this subject) began to build their own devices. It proved to be a false dawn. In a highly controversial episode lasting several years, the new detector groups all failed to replicate Weber’s results with their instruments (Collins 2004). Nevertheless, despite this controversial and turbulent start, most of these groups continued in the field, persisting through decades of hard effort and many different instruments. Today it is widely expected that the first direct detection of gravitational waves will take place within the decade.

As an illustration of how likely the detection of gravitational waves was thought to be in earlier years, one of the most dedicated boosters of the effort, Kip Thorne, had no difficulty in 1981 in finding a taker for a wager that gravitational waves would be detected by the end of the last century. The wager was made with the astronomer Jeremiah Ostriker, one of the better-known critics of the large detectors then being proposed. Thorne was one of the chief movers behind the largest of the new detector projects, the half-billion-dollar Laser Interferometer Gravitational Wave Observatory, or LIGO. He lost the bet, of course. One can see the record of it posted in the west corridor of the Bridge Building at the California Institute of
Figure 1.1. The LIGO facility at Hanford, Washington, one of two separate detectors in the LIGO system. This Laser Interferometer Gravitational Wave observatory consists primarily of two 4-km beam tubes down which lasers are fired and bounced back and forth by high-quality mirrors. Any changes in the time taken for the light to travel along the tubes is possible evidence for the passage of gravitational waves. One of the two beam tubes can be seen receding into the distance. (Courtesy LIGO Laboratory)

Technology (Caltech), outside Thorne’s office. It stands beside more than half a dozen other such wagers between Thorne and his colleagues (the most famous of Thorne’s wagering friends is Stephen Hawking), most of which Thorne has won. On it is written his note of concession, “I underestimated the time required to make LIGO a reality.” It is actually more remarkable that he and others managed to make LIGO a reality at all, especially when one considers the controversial history of the field, for that controversy was not only on the experimental side. The theory of gravitational waves has an even longer history of disputes, false dawns, and setbacks. At one time or another, many theorists doubted whether such waves existed at all. Albert Einstein himself, who founded the theory of gravitational waves in 1916, numbered himself among the doubters on at least two occasions. How that controversy came to be replaced by the certainty and conviction necessary to motivate the great projects of today is the principal story of this book.
The ambivalent status of gravitational waves within physics at the time of the Weber controversy (the early 1970s) is expressed in the following comments relating to Weber’s claims from the National Academy of Sciences report *Astronomy and Astrophysics for the 1970s*. This report was written in 1971 as a guide to U.S. government funding agencies, in particular the National Science Foundation, for the decade ahead:

The detection of gravitational waves bears directly on the question of whether there is any such thing as a “gravitational field,” which can act as an independent entity. All actively pursued gravity theories deal with the concept of a gravitational field, so the mere existence of gravitational waves does not exclude any of these theories. Thus this fundamental field hypothesis has been generally accepted without observational support. Such credulity among scientists occurs only in relation to the deepest and most fundamental hypotheses for which they lack the facility to think differently in a comparably detailed and consistent way. In the nineteenth century a similar attitude led to a general acceptance of the ether and atoms decades before the experiments that abolished the ether and confirmed the atom.

The basic style of all physics so far in the twentieth century has been set by the field concept, which arose in electromagnetic theory to replace the vanished ether. This idea has been so overwhelmingly convincing, when tested in experimental and industrial applications, that scientists have tried to package every other known fundamental domain of physics in the same mold. Field theory is incontrovertibly successful in the case of the electromagnetic field. Application of field concepts to particle physics has been successful in many respects, but there are still many unresolved problems. Confirmation of the gravitational wave experiments would show that this concept is suitable for at least one of the other areas—that of gravitational phenomena—in which it is customarily employed. (pp. 282–283)

Thus belief in the existence of gravitational waves, while unsupported by any physical evidence as of the early 1970s, nevertheless prevailed among most physicists because they could see no alternative to modeling the gravitational force other than by analogy with the field theory that described electromagnetic theory. In 1916, shortly after his discovery of the field
equations of general relativity, Einstein became the first to describe gravitational waves within a complete field theory of gravity. Beginning with his approach, relativity theorists looked to various analogies with the electromagnetic field as they attempted to construct a theory of gravitational waves in the absence of experimental evidence. Along the way, disputes arose over the theoretical description of this phenomenon and even over whether the theory predicted its existence at all. Given this skepticism, it is not surprising to find that some relativists regarded the analogy underpinning faith in the orthodox picture of gravitational waves as inadequate. It is interesting to examine the views of those whose skepticism made them defy the consensus understanding of a hypothesis without which modern physicists lacked “the facility to think . . . in a . . . detailed and consistent way.”

How is it that an idea can be universally, or at least “generally,” held in science “without observational support?” To most ears, whether they belong to scientists or lay people, this does not sound terribly scientific. However, such a state of affairs is actually not uncommon in science, because it does happen that an extremely useful concept (e.g., that of a “field” of force), which is designed to provide an underlying explanation for observed phenomena, may arise without itself necessarily being detected or detectable. The case of gravitational waves is admittedly a little more unusual. In this case, we have a phenomenon that is suggested by the field concept as something whose effects on matter should be detectable. However, the phenomenon has never been detected and has been without even indirect evidence for decades, yet widespread belief in its existence persists. Some rather powerful motivation must lie behind this belief, and if we look for it, we find that the force behind this extraordinarily tenacious scientific belief is that of analogy. Specifically, the analogy in question is between the gravitational field, which underlies our modern theory of gravity (general relativity), and the electromagnetic field, which originated in the work of Michael Faraday and James Clerk Maxwell in the nineteenth century and which is the centerpiece of modern physics. The most dramatic prediction and confirmation of Maxwell’s theory was the existence of radio waves, which are part of a spectrum of electromagnetic radiation that actually includes light itself. The basic analogy here is that if gravity is described by a field theory, should it not also have waves which play the fundamental role in that theory as electromagnetic waves do in the theory of Maxwell and his successors?
The history of the field concept is itself a controversial one, dominated by arguments from analogy. Once the idea of electromagnetic radiation became widely accepted, nineteenth-century physicists naturally looked to analogies with other wave phenomena, like sound, which suggested that waves require a medium (such as air in the case of sound) to propagate in. No medium means no wave. The field concept became associated in the nineteenth century with the idea of the luminiferous ether, which was an invisible substance with bizarre properties that pervaded all of space and was the medium or carrier for the electromagnetic field. The old ether theory was discarded completely early in the twentieth century, and nowadays, insofar as we say that electromagnetic waves have a medium at all, we say that that medium is the electromagnetic field, an entity which is not even a part of the material world, although it is, of course, generated by particles that make up the material world. The electromagnetic field is generated only by particles which carry electric charge, but since energy has mass, all particles that exist (i.e., have energy) in the material world generate a gravitational field. Keep in mind, of course, that particles are themselves idealizations designed to help physicists model matter in their equations. In some sense we do not directly experience fields as real entities at all but instead observe their influence on the matter that surrounds us. Thus an electromagnetic wave exists for us only in so far as we have some device at hand that can absorb energy from it as it passes by.

Now how is it that such highly abstract ideas as fields of force have come to play so important a role in physics? It happened in stages, with the level of abstraction increasing at each step. This development went hand in hand with the increasingly dominant role of mathematics in physics. At one time, for instance before Newton, it used to be thought that physics, which was primarily involved with explaining the qualities of physical things, was not a very suitable discipline for the use of mathematics. One characteristic of modern physics since Newton has been an escalating mathematization of the subject. Indeed, Einstein’s introduction of general relativity played a major role in this process, as did Newton’s introduction of his gravitational theory in the Principia. A very important agent of this increasing abstraction has been the creative use of analogies. For instance, in ancient times Greek philosophers and Roman engineers proposed that sound was a kind of wave traveling through the air, drawing an analogy with the motion of waves on the surface of bodies of water. Via the physics of Aristotle,
this concept passed into the physics of the Middle Ages. At the time of Newton, through the work of his contemporary, Christiaan Huygens, and again in the nineteenth century, it was proposed that light was also a wave phenomenon, based on an analogy with the propagation of sound. At this stage the analogy was already becoming further removed from the immediate physical source of the metaphor, because advocates of the wave theory of light were more apt to make a comparison with sound rather than directly with water waves. The disconnection from direct physical experience increased greatly in the second half of the nineteenth century with the development of the Maxwellian theory of electromagnetic radiation, owing to the work of Maxwell, Heinrich Hertz, and others. A further stage of abstraction was added by the early relativity theorists in the first decades of the twentieth century, when they hypothesized that gravitational waves might exist in a field theory of gravitation. They based their analogy on the case of electromagnetic waves, already several stages removed from the kind of wave that we can actually see operating on the surface of water. Also, in this case, the extension of the analogy was being used to predict rather than to explain the existence of a new phenomenon. Some of the great drivers of change in twentieth-century physics were the discoveries of new forms of radiation and new particles, yet gravitational waves were to remain in a kind of limbo, predicted but not observed, for most of the century.

It is worth mentioning that the analogy with electromagnetism was a powerful tool for Einstein in his discovery of the field equations of general relativity. The route Einstein took to create this theory was a long and difficult one and has been extensively studied in recent years.1

Much has been written about analogies and their use in science (see especially Hesse 1966), but it is clear that there is no straightforward definition of what a scientific analogy is. Most analogies, like the one between gravitational and electromagnetic waves, could also be described as models. It is obvious that when physicists talk about gravitational waves being analogous to electromagnetic waves, they are thinking of the latter as a model for the former. The use of models is highly characteristic of physics, and in preferring the term analogy in this case, I am doing so because that is the term most often used by the physicists who work in this field. In addition I think it helps to clarify exactly what kind of model we are talking about. There are models that physicists hold to be actually true depictions of the thing being modeled, for instance, the kinetic model of gases, which
visualizes them as consisting of many tiny molecules. Nowadays physicists believe that this is exactly what gases consist of. A model may also be a kind of construction of many parts, each of them imaginary, but whose whole forms a functionally equivalent depiction of the thing modeled (what we have in mind when we speak of “model-building”). An example of this kind would include Maxwell’s attempts to model the luminiferous ether as a mechanical system of gears and cogs. In our case physicists do not believe that gravitational waves really are electromagnetic waves (though when the idea first emerged this seemed a real possibility), nor are they constructing a model from simple building blocks. They are saying that gravitational waves behave like electromagnetic waves and that there is often a point-for-point comparison to be made between the equations which govern each. This makes the word analogy a very apt term to describe what is going on, since when we talk about analogy we often understand by the term a set of correspondences between two systems, such that features of one system correspond to certain features of the other system. The analogy that physicists studying gravitational wave refer to is a rather formal, mathematically based analogy, which establishes that there are correspondences between the equations governing gravitational waves—and the quantities appearing in them—and the equations governing electromagnetic radiation. However, there are other analogies of interest to us that are more descriptive and informal in nature, such as claims that gravitational waves can be thought of as “ripples in the curvature of spacetime,” evoking water waves on the surface of a pond. To be clear I will use the term metaphor to describe this descriptive kind of analogy and try to reserve the term analogy for the more formal one that lies at the heart of my argument.

For our purposes we will focus on two main uses of analogy, the first of which is as a heuristic, or finding, device. In this case, one is not necessarily committed to making every point of the analogy correspond, because one is not supposing that the two entities are really the same thing. Thomas Kuhn has discussed the importance of this kind of analogy in the practice of physics, emphasizing what a critical role analogic thinking plays in enabling physicists to make the widest possible use of the tools available to them. Although physicists come to a new problem with a large repertoire of mathematical techniques for solving problems, it will not be immediately clear how best these techniques can be applied to the problem at hand (Kuhn 1977, pp. 306–7). Kuhn argued convincingly that looking for analogies
between the new problem and those solved successfully in the past is the chief way in which a physicist will try to deal with an unfamiliar topic: "Once that likeness or analogy [between the new problem and the old] has been seen, only manipulative difficulties remain" (Kuhn 1977, p. 305). The beauty of finding such an analogy is that it enables the physicists to unleash their arsenal of techniques, hard won through experience in other subjects, onto a new problem. But since, as Kuhn emphasized, the sort of analogy that is being exploited is by no means a strict set of correspondences, there is plenty of room for argument about the validity of the analogy. As another philosopher of science has said, "Arguments from analogy may be fruitful, but they are always invalid" (Mario Bunge; quoted in North 1981, p. 135). There is plenty of scope for being wrong in this business. In cases where the dependence on analogy persists for a (perhaps unusually) long period, we will not be surprised to find that it is fertile ground not only for discovery, but also for controversy.

Now an analogy may also be proposed in a situation where it is suspected that a real underlying structural connection exists between the two entities being compared (as in the case of the kinetic model of gases). In this case the analogy may be viewed as the first step on the road to unifying two areas of physics. Thus from the beginning, gravitational waves were seen as an element of a possible unified theory of electromagnetism and gravity. This made the argument from analogy appear much more compelling to some physicists. In addition there was another argument, based on special relativity, that was derived from the fact that the principle of relativity (which guided the development of special relativity) presumed that no signals could travel faster than light. If gravity proved an exception to this rule, then this might threaten the underpinnings of this important theory. Therefore the analogy in this case acquired great force because it appeared that if gravity did not behave analogously to electromagnetism, at least in regard to the speed at which the field was propagating, then it would entail great problems for Maxwell’s theory, which Einstein had only with difficulty reconciled to relativity theory.

The analogy on which wave theories are based naturally gave rise, as already mentioned, to attempts to identify a medium for phenomena like light and gravitational waves. When we look at waves in water we realize that the wave, though we can see it as a thing which moves and has its own reality, is at the same time nothing more than a disturbance in the water. It exists
within a medium through which it moves or propagates. The medium may move as part of the disturbance, but it is not the medium which is propagating, or traveling, with the wave. The wave that washes against the California shore is not made up of water molecules freshly arrived from Japan. The water is local; it is only the disturbance that has traveled across the sea, being handed on, as it were, from one part of the water to another as it goes. Similarly, sound is a disturbance in the air, through which it propagates. Sound is not like wind; it doesn’t move masses of air about but instead travels through it. What, then, is the medium that transmits or propagates electromagnetic and gravitational waves? The attempts to visualize the medium of electromagnetism in the nineteenth century as the luminiferous ether came to an ignominious end around the turn of the century amid failed attempts to detect any evidence for an effect on the behavior of light as it moved through the ether. If light had a medium, then its movement through the latter should surely affect its apparent speed, just as would be the case with waves in water. The famous Michelson-Morley experiment (among many other experiments) failed to detect any variation in the speed of light depending on whether it was moving into or along with the putative ether wind created by the motion of the earth. The luminiferous ether theory encountered increasing obstacles as the theory of electromagnetism developed, and Einstein dealt it a mortal blow with his special theory of relativity in 1905, which took as fundamental assumptions that the motion of all material bodies is relative, whereas light has the same velocity for all observers. He argued that without such an assumption the principle of relativity could not be consistently applied to all areas of physics. As this standpoint became the accepted one, it discouraged all attempts to treat the medium of light and other electromagnetic waves as a physical thing. As we shall see, the medium of gravitational waves, as presently conceived, is spacetime itself. The once abstract entities space and time take on a very active role in Einstein’s theory. This entire process went along with an increasing formalism, which saw a retreat from the kind of highly visual modeling that characterized Maxwell’s approach to the subject and a turn towards the feeling that it was only mathematics which mattered. In Hertz’s famous phrase, “Maxwell’s theory is Maxwell’s system of equations.” Thus we have the twentieth-century attitude in which physical models may not be entirely real, but equations certainly are, as expressed by the T-shirt, popular with scientists everywhere, which reads, “And God said, ‘Maxwell’s equations’ and there
was light.” This outlook, which to some extent reflects Einstein’s approach to physics in his later years, is characteristic of the physics of the last century.

Now we can discuss how all this talk of analogies is related to the theoretical “discovery” of gravitational waves. Let us give a brief summary of how it came about. First, we have Maxwell’s theory itself, which took a force known to obey an inverse-square force law and rewrote it as a new kind of theory, a field theory, in which an associated wave phenomenon played a central role. This must have naturally suggested a simple and not very compelling analogy that probably influenced a few people prior to 1900. But afterwards, during the period of relativity theory, in which electromagnetic waves and their speed of propagation were seen to play an absolutely central role in physics in general, the notion arose that surely gravity could not be left in its old Newtonian form. Since the speed of light now appeared as an absolute upper limit to the speed with which signals could travel, how could the gravitational force make itself felt at great distances instantaneously, as the traditional theory demanded? That the speed of light was an upper limit to the speed with which any signal could be transmitted was of central importance to Einstein’s demonstration that the new relativity transformations of the Maxwell-Lorentz equations also applied to the everyday science of motion, kinematics. This upper limit was at the foundations of the new theory of relativity. It seemed that the force mediated by the gravitational field must propagate at a finite speed (so that we feel the Sun’s gravitational pull on us only after the effect has had a chance to cross the space between us), and this impression naturally suggested the idea of an associated wave. The phrase gravitational wave (onde gravifique) was first coined by Henri Poincaré in 1908 in this milieu. The idea had clearly become highly suggestible, and once Einstein had found his set of equations for the gravitational field in 1915, he immediately turned to describe gravitational waves by a method designed to make his equations look and behave as much like Maxwell’s as possible. Thus the equations were the reality, and if the equations predicted the waves that the more metaphorical and less formal analogy suggested, then surely they must exist. The only remaining problem was that it was quickly recognized that the waves would be very hard, if not impossible, to detect on account of being very weak. Therefore an element of physical theory that seemed as if it must exist was nevertheless compelled to remain in the limbo of the unverifiable, as far as experiment or observation was concerned. But of greater relevance for
most of our story was that the equations were far from telling all they knew. Because of their great complexity, Einstein had been obliged to make use of an approximate method that was open to many criticisms. Thus over the years, researchers returned time and again to these alluring creatures, with a degree of optimism or skepticism that varied according to the physicist's personality. Einstein was far from saying the final word on the subject, but he had sown the seeds of a great controversy. He himself would later help produce the spark that would set the whole field ablaze.

It is worth mentioning at this point why the shorter term *gravity waves* was not used until recently to describe this phenomenon. The reason is that this term had already been coined to describe certain types of waves in water whose motion is determined by the water's own weight, or gravity, rather than by the surface tension, which governs what we call ripples. Gravity waves are the longer wavelength waves with the characteristic curving peaks that we are accustomed to seeing on a trip to the beach. This use of the term *gravity waves*, which has been around since the nineteenth century, has been only very slowly displaced by its current use as a handier term for gravitational waves. Obviously, the longer phrase is something of a mouthful, but for as long as gravitational waves remained the esoteric subject of theory only, there was little reason to shift the meaning of *gravity waves*. However, as the subject of fluid wave mechanics has declined somewhat in importance (probably because of the peak of perfection it reached concerning phenomena such as waves in water), and as gravitational wave studies have become increasingly important in the last thirty years, the phrase *gravity waves* has come to be generally used to refer to gravitational waves, though I will prefer the latter term.

It is the rippling waves characteristic of relatively short wavelength water waves that provide the usual kind of visual analogy with gravitational waves. Although, as we have discussed, there are several layers of abstraction lying between our visual impression of water waves and the idea of gravitational waves, physicists often find it useful to reach back to the original source of the metaphor when attempting to describe gravitational waves for a lay or student audience. Probably everyone has heard the expression that gravitational waves are “ripples in the curvature of spacetime.” Just as water ripples appear like smooth variations of curvature on a two-dimensional sheet, we expect gravitational waves to consist of curvature in the spacetime sheet (which is, of course, four-dimensional). Thus although the formal analogy
with electromagnetic waves has played a much bigger role in the development of the theory of gravitational waves, the ripples metaphor, with its far greater visual appeal, has come to prominence in recent times in popular exposition. Interestingly, it was not used a great deal in popular accounts before about 1970. It is almost as if physicists were careful about the use of strong metaphors until they themselves had attained a greater understanding of gravitational radiation. Before this time, even when addressing a lay audience, they preferred to stay fairly close to the electromagnetic analogy. As their confidence in their mastery of this new and purely theoretical phenomenon grew through the 1960s and early 1970s, they ventured into more colorful explanations. It is perhaps no coincidence that this is also the period in which the first real hopes of experimental detection emerged. It was only when gravitational waves drew closer to the real world of observations that they could be described in terms of more concrete analogies with everyday experience.

I will use the term skeptic, as it was used by many relativists in this context, to describe those theorists who either doubted the existence of gravitational waves altogether or, more commonly, thought they would not be emitted by freely falling gravitational systems, such as binary stars, which today are considered the sources most likely to be observed by the new detectors. Although this use stretches the term to cover dozens of theorists over many decades from the 1920s to the 1980s, there is one attitude that seems common to each of them: their skepticism of the analogy with electromagnetism, which they regarded, for various reasons, as an inappropriate or misleading model on which to construct a theory of gravitational radiation. They were aware of the compelling force that this analogy had for many of their peers, as one leading skeptic, Leopold Infeld, made clear in his autobiography:

It is therefore apparent that the existence of gravitational waves can be deduced from general relativity just as the existence of electromagnetic waves can be deduced from Maxwell’s theory. Every physicist who has ever studied the theory of relativity is convinced on this point. (Infeld 1941, p. 261)

Nevertheless, although most of the skeptics accepted that the field concept was appropriate for gravitation, they were wary of assuming too many parallels between the gravitational field and the electromagnetic field.
The skeptics did not ignore the analogy; in fact, they often addressed it in their papers at greater length than did nonskeptics, but they did so critically. It also guided their thinking on the radiation problem, but in a different way from the use made of it by nonskeptics. Whereas nonskeptics emphasized the points of similarity between the two theories, thereby enabling them to adopt insights, intuition, and calculational tools borrowed from the better understood electromagnetic theory of radiation, the skeptics tended to focus on those points at which the analogy broke down, and they did so not merely for rhetorical purposes. An analogy that is perfect in every detail lacks the fertility which permits new insight into the nature of the new phenomenon to be developed. There must be a point where the new, unfamiliar theory becomes distinguishable from the old and takes on its own life and reality. As an example, the quadrupole formula, whose history we will discuss later at great length, describes the rate of energy loss by a source of gravitational waves. It can be derived by a calculation that is analogous to those used in the case of electrodynamics, and the result itself bears comparison with similar results in the case of an electromagnetic transmitter. But there is a striking difference in the gravitational case, which is indicated by the name of the formula itself. For gravity waves, quadrupolar radiation (meaning emission by a system with motions about two separate axes of symmetry, as opposed to one in the case of dipole radiation) is the lowest order of emission, whereas electromagnetic waves exist with dipole symmetry. In fact, our experience of electromagnetic radiation is dominated by dipole sources, and anyone with some experience with radio antennae knows what a dipole is. But gravitational dipoles do not emit waves, which is one of the reasons why gravitational waves are so weak that detecting them has been a mammoth billion-dollar enterprise which is still in progress.

Therefore, a successful analogy must not only exhibit many appropriate parallels between the two objects of comparison, but in order to be fruitful, it must also have points at which the comparison either breaks down or becomes less than straightforward. Given this requirement, one can expect to see different styles of analogic reasoning, in which greater or lesser emphasis is placed on the analogy or its breakdowns. I see the skeptics—among whom I number Infeld, Peter Havas, Arther Stanley Eddington, Nathan Rosen, Hermann Bondi, and others—as those who employed the analogy with electromagnetism in a negative way, while others—such as
John Wheeler, Lev Landau, and Felix Pirani—preferred a more positive use of the analogy. Both approaches are fertile, and the skeptics, who for a time included Einstein himself, made many contributions to the evolution of gravitational wave theory. This is especially true of Bondi, who, in direct contrast to that of a nonskeptic, exhibited his style of analogic reasoning in the following encounter with Wheeler, from the Chapel Hill conference *Conference on the Role of Gravitation in Physics* in 1957. This exchange gives a perfect illustration of the contrast in the positive and negative styles of using analogy. Introducing the session, Bondi remarked:

> The analogy between electromagnetism and gravitational waves has often been made, but doesn’t go very far, holding only to the very questionable extent to which the equations are similar. The cardinal feature of electromagnetic radiation is that when radiation is produced the radiator loses an amount of energy which is independent of the location of the absorbers. With gravitational radiation, on the other hand, we still do not know whether a gravitational radiator transmits energy whether there is a near receiver or not. (DeWitt 1957, p. 33)

Clearly, to Bondi the formal analogy between the equations of general relativity and those of electromagnetism (between the Einstein equations and the Maxwell equations), which had first been emphasized by Einstein himself, was not very compelling. He was looking for a more intuitive use of analogy and appeared to find the negative aspects of the comparison more illuminating than the positive ones.

Bondi was interested in the question of whether a person taking exercise by waving two dumbbells around in an unpredictable fashion transmits gravitational waves that carry both energy and information. Note that Bondi doubted that a system of masses moving in a predictable way, such as a man falling or a binary star system (the two elements of which are essentially falling towards each other), could radiate energy. He did carry the analogy with electromagnetism so far as to show that an induction of energy in one systems of masses by a nearby one was possible in gravitation. In his presentation at Chapel Hill he discussed whether a cylindrically symmetric system could lose mass as a result of the emission of gravitational waves. He concluded by answering his opening question (above) in such a way
as to emphasize differences between the electromagnetic and gravitational fields:

“To my mind the electromagnetic field is like money spent. I do not get it back unless someone is very charitable. The gravitational field is more like my breathlessness when I do my exercise. When I stop, I regain my breath. If I do not stop (as in the periodic case) I will collapse. In the finite case, which to my mind is the more physical one, no irreversible change has taken place.” (DeWitt 1957, p. 36; quotation marks in original)

(For many of the people I interviewed for this book, the image of Bondi doing his exercises to generate gravitational waves was their strongest memory of this conference and others of the period.)

Bondi had presented the case of a cylindrically symmetric system as an example of a system in which the gravitational field does not radiate although it can transmit energy by a form of induction, in analogy with electromagnetic induction. John Wheeler’s response to this was to find a deep analogy between the two fields, precisely where Bondi perceived a critical difference:

“How one can think that a cylindrically symmetric system could radiate is a surprise to me. There seems to be a far-reaching analogy between this case and the problem of emission of electromagnetic radiation from a zero-zero transmission in an atom or nucleus. The charge can oscillate spherically symmetrically, but the system doesn’t radiate. However, if we have an electron in the neighborhood, internal conversion can take place, with still no electromagnetic radiation emitted. This could correspond to the uptake of energy of the gravitational disturbance created by the ‘cylindrical symmetric’ exercise of yours.” (DeWitt 1957, p. 36; quotation marks in original)

In response to this, Bondi agreed “he has had suspicions on that side also. To put it crudely, what stops the electromagnetic radiation in the atom is the law of conservation of charge, and what stops gravitational radiation from taking place is the conservation of mass and of momentum. But he does not think there is necessarily anything against radiation of cylindrical symmetry” (DeWitt 1957, p. 36). Note that although the conservation of mass is analogous to conservation of charge, there is no direct electromagnetic
analog of conservation of momentum. Bondi reworded Wheeler’s example in such a way as to point up the dissimilarity between the two cases, rather than Wheeler’s “far-reaching analogy.”

In the closing remarks for the session, Wheeler elaborated on the analogy between the two fields, nicely summing up the nonskeptic’s view of gravitational waves:

As concerns the radiation problem, we would like to know what is the highest degree of symmetry one can have in a problem, and still have interesting radiation. This leads one to the question of whether, even in the cases where there is no symmetry, one has reason to expect radiation. On this score, it would be well to recall an important physical fact: that the gravitational field of a point charge has close analogies to the electrical field. One knows that there is a certain linear approximation to the field equations similar in nature to the electromagnetic equations, so that if a mass is accelerating, one finds it produces radiation similar to the electromagnetic radiation of an accelerating charge. On this account, one expects gravitational radiation. Using this analogy, Einstein was able to calculate the rate of radiation from a double star. (DeWitt 1957, p. 45)

As we shall see, it is a characteristic of skeptics, from Eddington by way of Bondi to Havas, to deny that Einstein’s calculation can be applied to the case of a binary star system.

Wheeler went on to address Bondi’s earlier remarks, once again recasting them with a positive spin on the electromagnetic analogy:

**BONDI** has reminded us that if one looks for radiation pressure on a particle in gravitational waves, he must take into account the radiation produced by the motion of the particle itself. The situation here is analogous to an electromagnetic wave passing over a particle. To the lowest approximation, the particle only feels the electric field and oscillates with it. If one improves his approximation, he finds that the particle begins to respond to the magnetic field, and moves in a figure eight. Still there is no radiation pressure. It is only when one includes the radiation that the particle itself gives out that one gets radiation pressure. That is, it is only when one allows for the radiation damping force that one finds the particle moving forward. Similarly,
in the case of gravitational radiation, one faces similar problems. As "weber brought out [referring to an earlier talk by Joseph Weber, the pioneer of gravity wave detection already referred to], in the case of a cylindrical wave, a gravitational metric charge passing over a particle leaves the particle with its initial energy after the disturbance has left. At first sight, one might believe that there is no observable consequence of the action of the wave on the particle. However, the electromagnetic analogy suggests that if one were to go further, one might expect to find radiation pressure. (DeWitt 1957, p. 45)

Wheeler’s instinct was to press forward with the analogy, refusing to let go of a useful guide, until all basic problems of understanding gravitational waves had been overcome. Obviously his approach tended to presume their existence, and others preferred to remain agnostic, feeling their way forward, on the lookout for breakdowns in the analogy, fearing that over reliance on it might lead them into pitfalls of understanding.

So in this amusing and revealing interchange, for every similarity between the two fields, electromagnetic and gravitational, seen by Wheeler, Bondi saw a dissimilarity. For every confirmation of the analogy, as Wheeler would have had it, Bondi saw it, on the contrary, breaking down. Which one was right? In fact, Bondi and Wheeler had among the keenest intuitions on the workings of the gravitational field of all the relativists of that time. They and their groups contributed more than any others to the understanding of the phenomenon of gravitational waves that emerged in the years after this interchange. Nevertheless, there was a clash of styles apparent in their approaches to the problem. The question of the analogy between electromagnetism and gravity lay at the heart of the problem of gravitational waves. In general, the skeptics were those who doubted or mistrusted the analogy and used it gingerly and with caution. That they nevertheless used it is, as I said, an important point to keep in mind. Bondi was clearly using the analogy as a guide about as much as Wheeler was, but he was searching for different things. He eagerly looked for the point of breakdown, seeking it out, in the hopes of finding the new and unexpected. Wheeler was hoping to ride the analogic horse as far as it would take him into strange new worlds of physics, beyond experiment but not beyond the imagination. Their methods differed, but their motivation was the same.