Abstract  We distinguish three historical and scientific views of matter, spacetime, and the relationship between them: the absolute approach of Newton, the relational approach most often associated with Mach, and a third, geometrical approach which inspired Einstein and continues to drive efforts toward a unified theory of fundamental interactions today. Which is correct? We suggest that this is, to a large extent, an “ill-posed question,” reminiscent of the wave/particle debate in earlier times. The boundary between matter and spacetime is no longer easy to draw, and it is likely that they are complementary aspects of the same reality. There is no clearer illustration of this than the modern view of the vacuum. We review the importance of this concept in cosmology, and explore the extent to which the old idea of an “empty” vacuum might still be maintained. If the real cosmological vacuum is far from empty, as observations now suggest, then it may be possible to achieve an even simpler goal: a Universe with a net energy of zero.

For all the world’s a stage, and we are merely players.

Shakespeare, As You Like It

Matter and spacetime

Matter in its various guises is often thought of as an actor, moving about on the stage of space and time. It is of course an open question, whether such a dichotomy between “thing” and “place” really has a counterpart in external reality, or whether it is merely a way for human minds to sort and order their sensory experiences. We will not try to settle this old debate here. Instead we review some of the ways in which it has been approached by physicists and, most recently, cosmologists.

Some thinkers, of course, have gone so far as to deny that either matter or spacetime correspond to anything outside the mind. By and large physicists would react impatiently to such a view, sympathizing perhaps with Samuel Johnson, who struck his foot against a large stone and declared, “I refute it thus.” Most have in fact tended to go to the opposite extreme, accepting both matter and spacetime as real and apparently independent facts of existence, without inquiring into the question more deeply. Newton (1687), for example, took it as axiomatic that “absolute, true and mathematical time, of itself and from its own nature, flows equably without relation to anything external,” and that “absolute space, in its own nature, without relation to anything external, remains always similar and immoveable.” He added that the latter’s existence could be demonstrated empirically by hanging a bucket of water from a rope and spinning it (Fig. 1). The fact that the water’s surface gradually assumed a concave shape showed that it was spinning with respect to something; how else would it know what to do? Proof of the reality of space, in other words, could be found in the inertia of matter. Nowadays, Newton might point to the Earth’s oblateness as another example: what tells the planet how much to bulge, if not its rotation with respect to absolute space? This Newtonian or absolute view is still part of the modern physics curriculum, as any student struggling with “fictitious forces” can attest.¹

¹ Also known as “noninertial forces,” these have to be added to Newton’s Laws of Motion in frames of reference which do not move uniformly with respect to absolute space; otherwise the laws no longer describe real, physical processes (such as cyclones on the surface of the spinning Earth).
and its derivatives, which by the Einstein tensor \( G_{\mu\nu} \)
make up the left-hand side of Einstein’s gravitational field equations. These may be perfectly well-behaved,
regardless of whether or not there is a material source
term, or energy-momentum tensor \( T_{\mu\nu} \) on the right-hand
side of the equations. Spacetime, in other words, has a
skeleton of geometrical structure, whether or not it is
clothed in flesh-and-blood matter. Indeed the vacuum so-
lutions of general relativity, such as Minkowski space
and the Schwarzschild solution, are among the most rout-
tinely used. Einstein (1920) himself called empty space
the “new ether of general relativity,” writing: “Der Äther
der allgemeinen Relativitätstheorie ist ein Medium, wel-
ches selbst aller mechanischen und kinematischen
Eigenschaften bar ist, aber das mechanische (und ele-
kromagnetische) Geschehen mitbestimmt... Dieser Ät-
her darf nicht mit den für ponderable Medien char-
erischen Eigenschaften ausgestattet gedacht werden,
aus durch die Zeit verfolgbaren Teilen zu bestehen; der
Bewegungsbegriff darf auf ihn selbst nicht angewandt
werden.”

In spite of the last of these lines, it has since been
shown that the concept of motion, too, can be applied
to absolute space. The best-known solution of Einstein’s
field equations with this property, found by Kurt Gödel
(1949), describes a universe whose distant reaches rotate
endlessly around the sky without inducing inertia in
the matter it contains. In such a world, we would have to
pirouette continuously with respect to the “fixed stars,”
in order to keep our arms hanging at our sides. As it turns
out, our Universe does not rotate in this manner – but
in principle, it could. The observed fact that distant masses
stand still in our local inertial frame is in fact something
of a coincidence in the context of general relativity.5
And the existence of such solutions demonstrates the per-
sistence of absolute spacetime in Einstein’s theory.

One phenomenon which is sometimes thought to
“prove” the existence of absolute space is the motion of
the Earth relative to the rest frame of the cosmic micro-
wave background radiation (CMBR). As measured with

gravitational field, one can always find a “locally
inertial reference frame” in which it disappears (at least on small
scales). Near a massive body such as the Earth, an iner-
tial frame is one which does not accelerate in
any direction. Accelerate with respect to what? There is
no answer to this question within general relativity, any
more than in Newton’s theory of gravity. To see if one is
in a noninertial frame, one checks whether the laws of
special relativity are satisfied – just as Newton could tell
whether he was moving uniformly with respect to absolute
space by checking whether Newton’s Laws of Mo-
tion were satisfied.

The operational definition of inertial frames as “those
in which general relativity reduces to special relativity”
may hint at an a priori basis for distinguishing between
inertial and noninertial frames in Einstein’s theory. The
special theory is indeed unique, not least in the fact that
it lies at the core of electromagnetic theory. Of the four
forces of nature, electromagnetism is far and away the
most important on the scale of human beings and their
sensory and experimental apparatus. We are so con-
structed, in other words, that special relativity governs
our perception of the world. Perhaps this fact plays a role
in picking out the frames we call inertial. If it were not
so, processes such as measurement, perception, and cog-
nition itself might conceivably be quite different, per-
haps impossible. One does not like to think that our sta-
tus as human observers could influence the structure of
the scientific laws we discover. Nevertheless there are
serious historical antecedents for such an idea.2

Mathematically, absolute spacetime enters into the
general theory of relativity through the metric tensor \( g_{\mu\nu} \)

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2 Examples range from quantum measurement theory (e.g., Rae 1990) through the work of Arthur Eddington (1939; see Wesson 2000 for review) to the anthropic principle in modern cosmology (Barrow and Tipler 1986).

3 “The ether of general relativity is a medium which has no me-
chanical and kinematical properties, but nevertheless co-deter-
mines mechanical and kinematical phenomena... This ether should
not be thought of as having the characteristics of ponderable mat-
ter, or consisting of time-dependent parts. The concept of motion
must not be applied to it.”

4 Any such large-scale rotation rate, known as vorticity in a homo-
genous universe, can be strongly constrained by the small size of
anisotropies in the cosmic microwave background radiation
(Hawking 1969).

5 As we will see in the following section, calculations of Thirring
and others go some way toward explaining this coincidence. A pe-
riod of accelerated expansion known as “cosmic inflation” in the
early universe may also help (Ellis and Olive 1983). Alternatively,
if the Universe is closed, the puzzle might be resolved by taking
the angular momentum of gravitational waves into account (King
1995).