Magnetic Tape

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We have all seen magnetic tape, at least in movies. However, now, the thing which comes to our mind when we say music or video is smartphones or cameras. Not long ago, magnetic tapes were the dominant medium for creating and storing audio-visual data and have been around for over a century.

Before understanding the magnetic tape and its working, I am going to explain the basic principles of Ferromagnetism and Faraday's First Law:-

Ferromagnetism

The electron spinning around the nucleus acts like an atomic dipole. For paramagnetic and diamagnetic materials, the alignment of atomic dipoles is maintained by a magnetic field from the outside. If B is removed, M disappears.
However, ferromagnets don't require any such external B to maintain M. The alignment of the atomic dipoles is frozen.
A critical property of a ferromagnet is that each dipole “likes” to point in the same direction as its neighbors. The reason for this preference is essentially quantum mechanical.

- The dipole moment comes from the fundamental property of the electron, which has quantum mechanical spin. Due to its quantum nature, the electron's spin can be in one of only two states, with the magnetic field either pointing "up" or "down". The spin of the electrons in atoms is the primary source of ferromagnetism. When these magnetic dipoles in a piece of matter are aligned (point in the same direction), their individually tiny magnetic fields add together to create a much larger macroscopic field.
- Reason: When two nearby atoms have unpaired electrons, whether the electron spins are parallel or antiparallel affects whether the electrons can share the same orbit due to the quantum mechanical effect called the exchange interaction. This affects the electron location, the Coulomb (electrostatic) interaction, and thus the energy difference between these states.
- When the orbitals of the unpaired outer valence electrons from adjacent atoms overlap, the distributions of their electric charge in space are farther apart when the electrons have parallel spins than when they have opposite spins. This reduces the electrostatic energy of the electrons when their spins are parallel compared to their energy when the spins are antiparallel, so the parallel-spin state is more stable.
- In simple terms, the outer electrons of adjacent atoms, which repel each other, can move further apart by aligning their spins in parallel, so the spins of these electrons tend to line up.

Materials made of atoms with filled electron shells have a total dipole moment of zero: because the electrons all exist in pairs with opposite spin, every electron's magnetic moment is canceled by the opposite moment of the second electron in the pair. Only atoms with partially filled shells (i.e., unpaired spins) can have a net magnetic moment, so ferromagnetism occurs only in materials with partially filled shells.

Domains:

> The above reasoning suggests that every piece of ferromagnetic material should have a strong magnetic field, since all the spins are aligned, yet iron and other ferromagnets are often found in an "unmagnetized" state.
> This is because a bulk piece of ferromagnetic material is divided into tiny regions called *magnetic domains*. Within each domain, the spins are aligned, but (if the bulk material is in its lowest energy configuration; i.e. *unmagnetized*), the spins of separate domains point in different directions, and their magnetic fields cancel out, so the object has no net large scale magnetic field.
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> Thus, a piece of iron in its lowest energy state ("unmagnetized") generally has little or no net magnetic field. However, the magnetic domains in a material are not fixed in place; they are regions where the spins of the electrons have aligned spontaneously due to their magnetic fields, and thus can be altered by an external magnetic field.
> If a strong enough external magnetic field is applied to the material, spins of the electrons align, thus reorienting the domains. Now, most of the dipoles are aligned with the external magnetic field.
> The domains will remain aligned when the external field is removed, creating a magnetic field of their own extending into the space around the material, thus creating a "permanent" magnet. The domains do not go back to their original minimum energy configuration when the field is removed because the domain walls tend to become 'pinned' on defects in the crystal lattice, preserving their parallel orientation.

Heating and then cooling a magnetized material, subjecting it to vibration by hammering it, or applying a rapidly oscillating magnetic field tends to release the domain walls from their pinned state, and the domain boundaries tend to move back to a lower energy configuration with a less external magnetic field, thus *demagnetizing* the material.

Faradays Law of Electromagnetic Induction

Through several simple experiments, Faraday figured out that relative motion between the magnet and the coil induced a current in the loop. By combinations of experiments, he concluded that “A changing magnetic field induces an electric field”.

- $$\mathcal{E} = \oint \mathbf{E} \cdot d\mathbf{l} = -\frac{d\Phi}{dt},$$

- The EMF induced in the loop is equal to the rate of change in flux

Whenever (and for whatever reason) the magnetic flux through a loop changes, an emf

$$\mathcal{E} = -\frac{d\Phi}{dt}$$

- **will appear in the loop.**

Coming back to our magnetic tapes, let us see the structure of the tape:

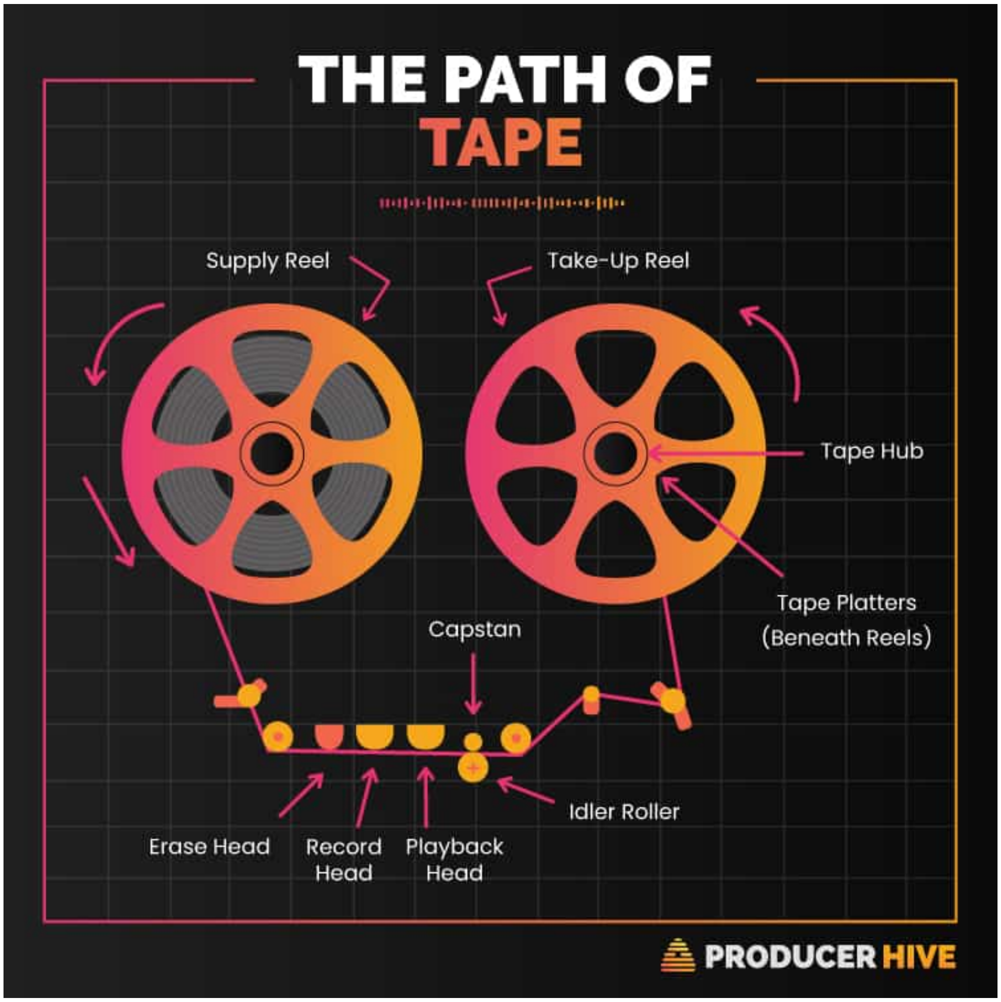
Structure of the tape

- Tape:
  The tape consists of three layers: a top coat, a substrate in the middle, and a bottom coat. The top coat consists of a magnetic pigment held together by a binder. The magnetic pigment consists of a ferromagnetic substance like ferrous oxide, chromium dioxide, or pure iron. The pigment provides small magnetic domains that can be manipulated to create and store signals.
  The magnetic pigment is added to give the magnetic particles their color. Stabilizers and lubricants slow the tape's deterioration and help it slide along the tape path. The binder adheres the magnetic particles to the base.
  The bottom coat is optional. If it is present, black matting is used to prevent the build-up of electrostatic charges due to constant relative motion between the tape and tape head.

- Tape Head:
  The tape-head consists of three sub-heads: A read head, a write head, and an erase head. All three heads are composed of a ferromagnetic ring with a slit at the bottom where the head meets the tape below (doesn't make physical contact). Coils of wire are wound around all three heads.

- Tape Guide:
  Tape guides, on both the sides of tape heads, are stationary posts that keep the tape at the proper height. They touch the tape, providing mechanical tension.

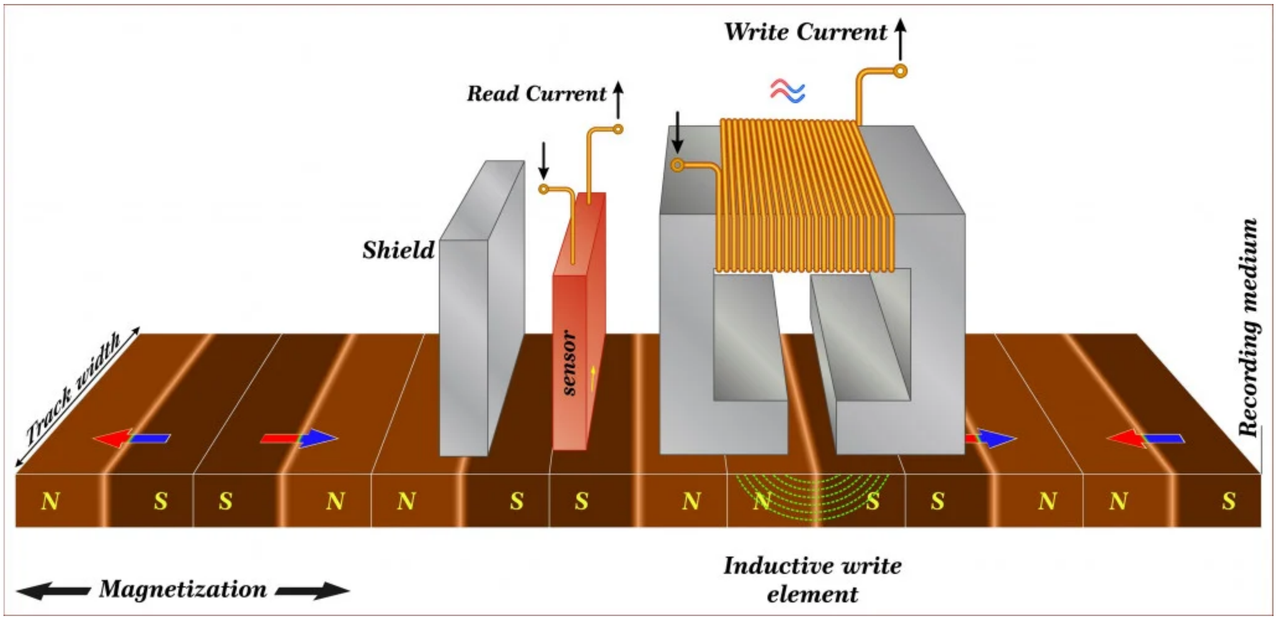
The blank tape has unaligned magnetic particles and domains. Unmagnetized particles point in random directions. Their individual magnetic fields cancel each other out, so there's barely any magnetic flux (force).



Audio Recording

- An electrical transducer converts audio input to electrical signals(it also works on the principle of electromagnetic induction)
- The varying current will set up a magnetic field in the recording head.
- The tape's top coat is fed to the write-head. The wire wound around the write-head carries the sound's electrical signature (current) to be recorded. The current-carrying wire induces a proportional magnetic field *M.*
- This magnetic field induces a residual changing magnetic pattern, as tape moves past its gap.
- The ferromagnetic ring ensures that the field *M* permeates the region without attenuation. The slit at the bottom of the ring (facing the tape) ensures that the magnetic field lines fringe out into the tape and completely magnetize the tape below it

- The pattern is proportional to the magnetic flux at the record head’s gap. The record head’s magnetic field strength determines how many particles become aligned in a given direction at any time.
- As the tape keeps moving, the tape guide on the left side feeds the un-magnetized tape into the write-head, and the magnetized part is received by the tape guide on the right side.

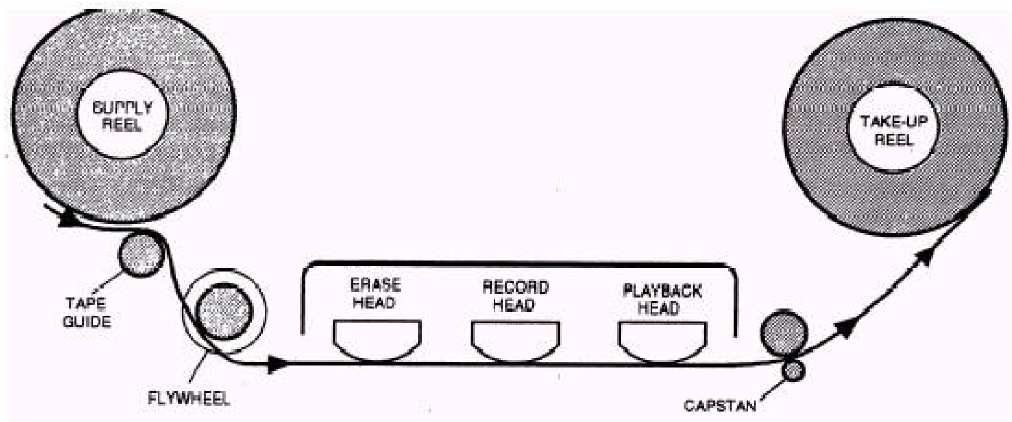


Audio Playback

- When monitoring from the playback head during playback, the gap detects a moving magnetic field, generating a current in the wire.
- The magnetized tape is fed into the read-head. The magnetic field of the tape pigments permeates the region and the ferromagnetic ring with a slit helps permeate the field without attenuation.
- A current is induced in the wire wound around the ring, which is proportional to the tape's magnetization.
- The wire is fed into a transducer, which converts the electrical signal into an audio signal.
- The tape keeps moving, and the successive magnetization patterns produce a corresponding audio output.

Fact: The supply reel holds the tape before it passes the tape heads when playing, recording, or fast-forwarding. The supply motor zips the tape back in fast rewind and maintains tape tension during fast forward. The take-up reel works the opposite way with its own motor – tape ends up here after passing the tape heads. Both reels have brakes to quickly (but gently) stop the tape.

During any fast winding (fast forward), tape lifters move the tape away from the tape heads so audio won't be heard as it zips past them. Also, it saves the tape heads from additional wear. Once fast winding is stopped, the tape lifters will retract by pressing stop or play so that the tape is again touching the tape heads.



Audio Deletion

- The magnetized tape is fed into the erase-head, which applies a changing high-frequency and a high-amplitude current, inducing a proportional magnetic field in the head. This field permeated the ferromagnetic ring into the tape, erasing the previous magnetization of the pigments.
- The erase head does precisely as the name implies. Its gap is wider than the ones found on the erase and record/sync heads. A very high frequency is fed into it while recording so the magnetic polarities of the tape's particles rapidly flip back and forth.
- When tape leaves the erase head's magnetic field's reach, the tape's particles, will have random magnetic polarities and be unmagnetized.

Advantages of Magnetic Tape Recorders:

1. Wide frequency range.
2. Low distortion.
3. Immediate availability of the signal in its initial electrical form as no time is lost in processing.
4. The possibility of erasing and reuse of the tape.
5. Possibility of playing back or reproducing the recorded signal as often as required without signal loss.

Applications of Magnetic Tape Recorders:

1. Data recording and analysis on missiles, aircraft, and satellites.
2. Communications and spying.
3. Recording of stress, vibration, and analysis of noise

Today, even tech giants like Google use magnetic tapes to archive data in clouds securely. Recently, IBM has also figured out how to store 200 GB on 1 sq inch tape.

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