Answer to Essential Question 20.1: In this case, the ranking is 2 > 3 > 4 > 1. Regions 2 and 3 have positive flux, because field lines directed out of the page pass through those regions. Region 4 still has a flux of zero, while region 1 has a negative flux because of the field lines passing through the region into the page.

20-2 Faraday's Law of Induction

Table 20.1 summarizes some experiments we do with a magnet and a loop of wire. The loop has a galvanometer in it, which is a sensitive current meter. When the needle on the meter is in the center there is no current in the loop. The direction and size of the needle's deflection reflects the direction and size of the current in the loop.
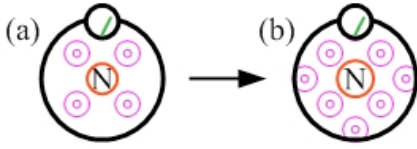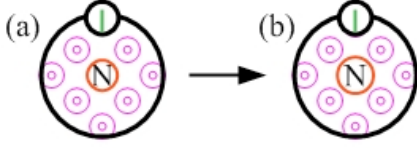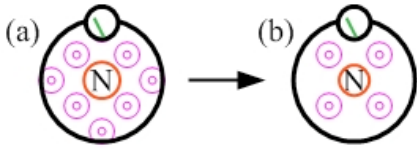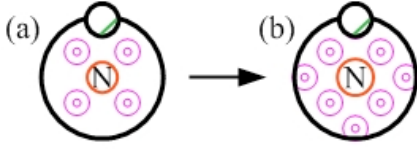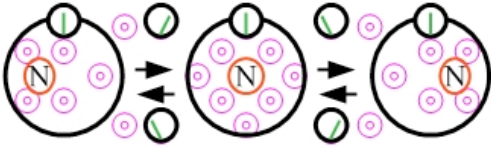
Experiment	Initial and final states	Meter reading
1. The north pole of the magnet is brought closer to the loop.	**Figure 20.5**: The loop initially has a small flux (a), which increases as the magnet comes closer (b).	*While the magnet is moving closer*, the meter needle deflects to the right.
2. The north pole is held at rest close to the loop.	**Figure 20.6**: The magnetic flux is large, but it is also constant the entire time.	The needle does not deflect at all.
3. The north pole of the magnet is moved away from the loop.	**Figure 20.7**: The loop initially has a large flux (a), which decreases as the magnet is moved away (b).	*While the magnet is moving away*, the meter needle deflects to the left.
4. The north pole of the magnet is brought closer to the loop, but at a faster rate than it was in experiment 1.	**Figure 20.8**: The same situation as Figure 20.5, but with less time between (a) and (b).	*While the magnet is moving closer*, the needle deflects farther to the right, but for less time, than in experiment 1.
5. The magnet is rotated back and forth in front of the loop.	**Figure 20.9**: The flux oscillates from large to small and back again.	As the magnet oscillates, the needle oscillates back and forth at, in this case, double the frequency of the magnet.

Table 20.1: Various experiments involving a magnet and a wire loop connected to a current meter. The views in the figures are looking through the loop at the magnet.

Among the conclusions we can draw from these experiments are the following:
- A magnet interacting with a conducting loop can produce a current in the loop.
- A current arises only when the magnetic flux through the loop is changing.
The current is larger when the magnetic flux changes at a faster rate.

Exposing a loop or coil to a *changing* magnetic flux gives rise to a voltage, called an **induced emf.** Following Ohm's law, the induced emf gives rise to an **induced current** in the loop or coil. The emf induced by a changing magnetic flux in each turn of a coil is equal to the time rate of change of that flux. Thus, for a coil with N turns, the net induced emf is given by:

$$\varepsilon = -N\frac{\Delta\Phi}{\Delta t} = -N\frac{\Delta\left(BA\cos\theta\right)}{\Delta t}.$$ (Eq. 20.2: **Faraday's Law of Induction**)

The minus sign in equation 20.2 will be explained in section 20-3.

EXPLORATION 20.2 – Using graphs with Faraday's Law

A flat square conducting coil, consisting of 5 turns, measures 5.0 cm × 5.0 cm. The coil has a resistance of 3.0 Ω and, as shown in Figure 20.10, moves at a constant velocity of 10 cm/s to the right through a region of space in which a uniform magnetic field is confined to the 20 cm long region shown in the figure. The field is directed out of the page, with a magnitude of 3.0 T.

Figure 20.10: A flat conducting coil moves at constant velocity to the right through a region of space in which a uniform magnetic field is confined. The small squares on the diagram are 5.0 cm on each side.

Draw the coil's motion diagram, and a graph of the magnetic flux through the coil as a function of time. Define out of the page as the positive direction for flux. Finally, draw a graph of the emf induced in the coil as a function of time. The diagrams are in Figure 20.11. For the first 1.0 s there is no flux, because no field passes through the coil. The flux grows linearly with time during the half-second the coil moves into the field. The flux is constant, at $B \times A = 7.5\times10^{-3}$ T m^2, for the next 1.5 s, and then drops linearly to zero in the half-second the coil takes to leave the field.

Faraday's Law tells us that the induced emf is related to $\Delta\Phi/\Delta t$, which is the slope of the flux versus time graph. While the flux is increasing, the slope of the flux graph is constant with a value of $\Delta\Phi/\Delta t = (7.5\times10^{-3}$ T m$^2)/(0.50$ s$) = 1.5\times10^{-2}$ V.
Multiplying by the factor of $-N$ from Faraday's Law, where $N = 5$ turns, gives an induced emf of -7.5×10^{-2} V. The induced emf drops to zero while the flux is constant, and then has a constant value of $+7.5 \times 10^{-2}$ V during the half-second period while the coil is leaving the magnetic field and the flux is decreasing.

Figure 20.11: (a) A motion diagram showing the coil's position at 1-second intervals. Graphs, as a function of time, of (b) the magnetic flux through the coil and (c) the emf induced in the coil.

Key idea: The induced emf is proportional to the negative of the slope of the graph of flux as a function of time.
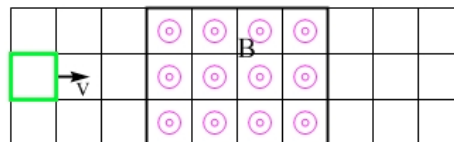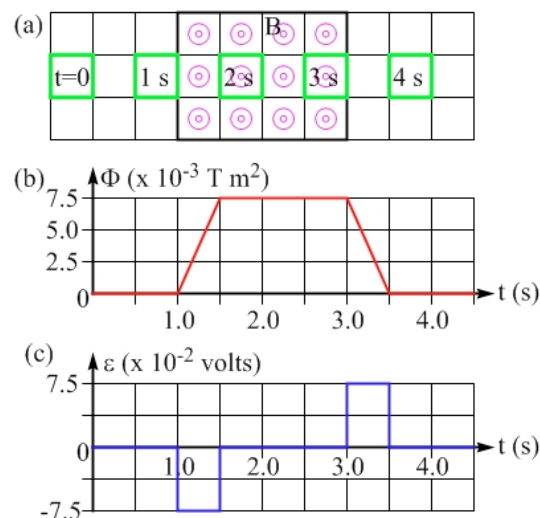**Related End-of-Chapter Exercises: 14 – 17, 23 – 26.**

Essential Question 20.2: What is the magnitude of the maximum current induced in the coil in the system described in Exploration 20.2?