The following explanation arose from a question from physics teacher Stephen Hill at Yanco Agricultural High School regarding transformers. Some of the material below, is slightly beyond the NSW syllabus, but this is included to provide teachers with some extra technical background.

This answer was formulated after discussion over these questions, between Stephen Bosi, Joe Khachan and Phil Dooley at the School of Physics, University of Sydney.

The question (slightly paraphrased) was:

Basic transformer theory is simple - ratio of turns, iron core, power in = power out (for ideal transformers etc) - but now the sticky bit. Assume you have a working transformer, current flows in the primary and the secondary. Now suppose the resistance of the secondary circuit is reduced. As an example, suppose you leave a 'plug pack' (transformer rectifier) plugged in and switched on with nothing attached to it (presumably little current being drawn from the mains) and then you attach your electric 'thing' to it (e.g. mobile phone, for charging) - how does the primary 'know' that something has been attached to the secondary??

What does this do to the secondary winding in the transformer such that it impacts on the flux in the core and eventually causes the current in the primary to alter (to rise, in this case). Simply saying "well the law of conservation of energy says it must" (or something similar) isn't really adequate for an inquisitive teenager - and I have a whole class load of 'em.

If I were explaining this to an undergraduate uni student rather than a high school student, I would be using an explanation containing the concepts of AC circuit theory, such as impedance, inductance, phase shift and so on. Here's my attempt to explain it using only concepts in the HSC & Prelim syllabus.

Section 1) First some background about how a coil differs from a resistor:

With a resistor, V = IR (Ohm's law). If you stick a voltage V across a resistor R, the current (nearly) instantaneously reaches the steady-state value of I = V/R.

1.1) This is NOT true of a coil. When you apply a voltage to a coil, the current doesn't reach its steady-state value immediately. Immediately after you apply a voltage (say, v_{app}) it forces the current in the coil to build up gradually. Initially the current is zero, but a current starts to flow in the direction of the applied voltage hence the resulting ***change* in current Δi points in the same direction as the applied voltage.**

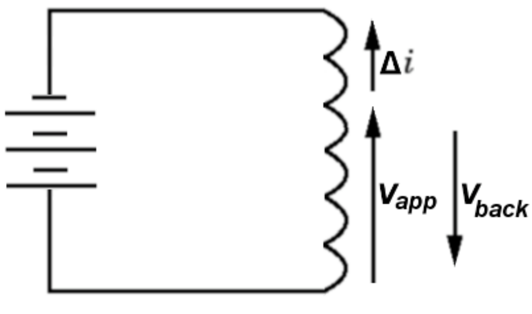

Figure 1.1: Changing current and back EMF in a coil*

1.2) Accompanying this changing current, of course, is a changing magnetic field. A changing magnetic field inside a coil will (by Lenz's law) induce an EMF in that coil that OPPOSES the change in current that produced this change in field and therefore (by paragraph 1.1) in the opposite direction (opposite sign) to the applied voltage. This EMF is called "back EMF" or v_{back}. This means that the net voltage across the coil is the applied voltage, minus the back EMF, or:

$$v_{net} = v_{app} - v_{back} \quad \text{Eqn 1.1}$$

1.3) In other words, the reason why it takes time for the current to build up to the maximum steady-state value, is because while the current is changing, there is a back EMF which reduces the net voltage v_{net} on the coil.

1.4) Eventually as the current approaches the steady-state value, the rate of change of current reduces and so v_{back} approaches zero, consequently the full applied voltage v_{app} finally appears across the coil and the current approaches its maximum. The more turns in the coil, the bigger the back EMF and the bigger will be the time delay to reach maximum current.

1.5) If instead you decrease the applied voltage on a coil that is already at maximum steady-state current, then for similar reasons, it takes time for the current to decrease. Just use the same Lenz's law argument but now for "decreasing" currents and fields - the back EMF now *reinforces* the (now decreased) applied voltage, to oppose the current decrease *i.e.*

$$v_{net} = v_{app} + v_{back}. \quad \text{Eqn 1.2}$$

By the way, for a coil connected to a DC applied voltage v_{app}, the maximum steady-state current is just given by Ohm's law, *i.e.* $i_{max} = v_{app}/R_{coil}$. If the applied voltage is AC, the coil typically doesn't have time to approach this maximum before the voltage changes.

Section 2) And now for the explanation about transformers:

A transformer only works with AC, so remember that all the voltages and currents I'm talking about will be changing all the time.

The first part of the explanation, you already know:

2.1) The oscillating applied voltage produces an oscillating current in the primary coil. Accompanying that oscillating current is an oscillating (*i.e.* changing) magnetic field. The changing magnetic field in the primary coil ALSO passes through the secondary coil (wound onto the same core) so by Faraday's law, it induces an EMF (voltage) across both coils. More about this later.

2.2) If the secondary circuit is OPEN (Fig. 2.1) then no secondary current can flow.

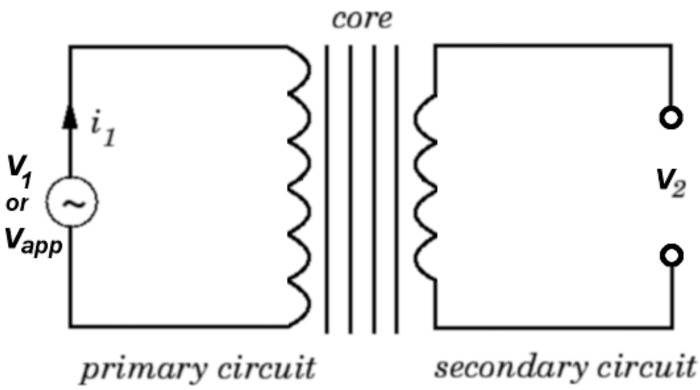

Figure 2.1: Open 2ndary circuit

2.3) ***Question:*** Why, when nothing is connected to the secondary circuit, is the current in the primary coil very small? (How does the primary coil "know" that nothing is connected to the secondary coil?).

2.4) Consider a particular moment in time when the applied oscillating voltage on the AC voltage source is v_{app} (or v_1). Because there is a voltage applied to the primary coil, it forces a change (Δi_1) in the current to occur. The change in current will be in the same direction as the applied voltage (as per paragraph 1.1).

2.5) The change in current Δi_1 through the primary coil, by Faraday's law, induces an EMF in the primary coil. By Lenz's law, the direction of this EMF is such that it OPPOSES the change in current that produced the changing magnetic field. This EMF is the "back EMF" or v_{back} and acts in the opposite direction to v_{app} (as described in paragraph 1.2).

2.6) Because of the large number of turns in a typical transformer, the back EMF will be almost as large as the applied voltage, so the net voltage across the primary coil is very small, or;

$$v_{net\ 1} = v_{app} - v_{back\ 1} \approx \text{very small} \qquad \text{Eqn 2.1}$$

so the current and changes in current through the primary coil will also be small.

2.7) Note: This change in primary current also produces a change in the magnetic field in the secondary coil (because both coils are wound around the same core). According to Faraday's law, the changing magnetic field *also* induces an EMF v_2 in the secondary coil.

2.8) Because no current can flow in the open secondary circuit, there is NO induced secondary current (or field) and so the secondary has a negligible effect on the primary coil. The primary coil is not connected electrically to the secondary, so the induced secondary EMF v_2 also has no effect on the primary. As far as the behaviour of the primary coil is concerned, when the secondary is open circuit, there may as well be no secondary coil.

Section 3) A transformer with a "load":

A "load" means something with a finite, non-zero resistance that allows current to flow and draws power out of a circuit. Imagine the transformer is now connected to an appliance (represented by the resistor in Fig. 3.1) which allows current to flow.

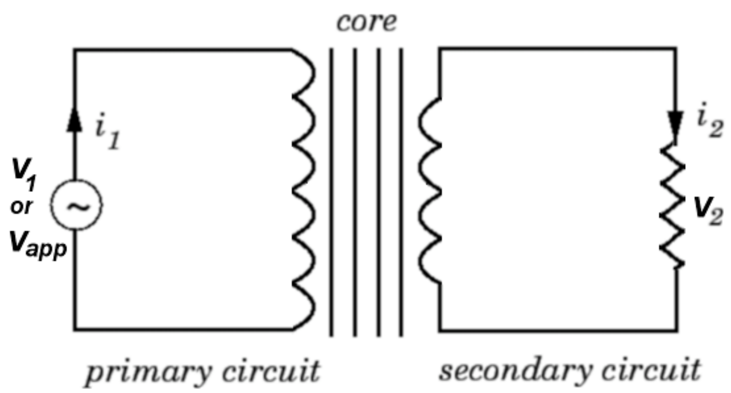

Figure 3.1: Closed 2ndary circuit

Question: When a load is connected to the secondary circuit, why does the current in the primary coil increase?

3.1) Re-read steps 2.1, 2.4, 2.5 & 2.7 in the explanation above. However, now a current can flow in the secondary coil.

3.2) The changing current in the primary coil produces a changing field in BOTH coils. This induces a back EMF in the primary coil $v_{back\ 1}$, but it ALSO induces an EMF in the secondary coil v_2. Because the secondary can now allow current to flow, v_2 forces a change (Δi_2) to occur in the secondary current.

3.3) The signs in the next bit are tricky - concentrate! Because both the primary back EMF $v_{back\ 1}$ and the secondary EMF v_2 are induced by the same change in field, they will point in the same direction. v_2 will the also force a change Δi_2 in secondary current which must point in the same direction as v_2 (as per paragraph 1.1) and therefore it points in the OPPOSITE direction to Δi_1. (*i.e.* Δi_2 and Δi_1 are of opposite sign*)

3.4) See Fig. 3.2. The change in secondary current Δi_2 ALSO produces an additional change in magnetic field in the core and hence induces *another* back EMF in the primary. Let's call this $v_{\text{back 2}}$. Since Δi_1 and Δi_2 are of opposite sign, $v_{\text{back 1}}$ and $v_{\text{back 2}}$ are ALSO of opposite sign. In other words $v_{\text{back 1}}$ opposes the direction of v_{app}, but $v_{\text{back 2}}$ reinforces the direction of v_{app}, or:

$$v_{\text{net 1}} = v_{\text{app}} - v_{\text{back 1}} + v_{\text{back 2}} \qquad \text{Eqn 3.1}$$

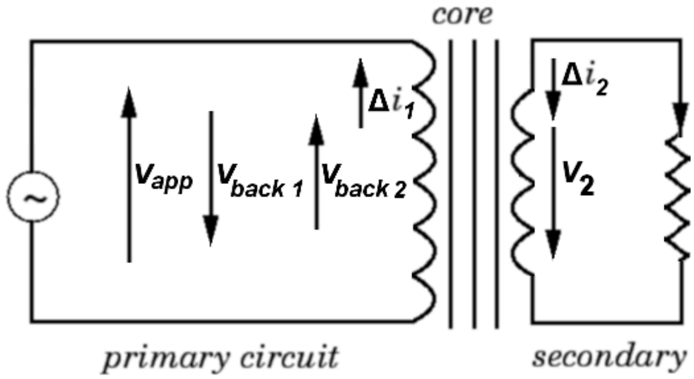

Figure 3.2: Changing current and back EMF in a coil*

3.5) Because $v_{\text{back 2}}$ partially cancels $v_{\text{back 1}}$, $v_{\text{net 1}}$ is now larger than it was in Eqn 2.1, so the primary current is also now larger - more power is drawn from the mains power into which the primary coil is plugged.

One final note beyond the syllabus: The coils will have a small resistance, but mostly are not acting like resistors. The reduction in current due to the back EMF shouldn't be thought of as resistance. Instead, it can be thought of as an AC version of resistance, called "impedance" which is not part of the HSC syllabus. Both capacitors and inductors (coils) exhibit impedance in AC circuits. However, resistors still do exhibit resistance in AC circuits.

*Please note! For simplicity, on these diagrams, I've marked in the directions of the currents and induced EMFs with up or down arrows. If taken literally, this is potentially misleading, because strictly speaking, the sign and directions of *i* and *v* in this discussion, should be expressed in terms of their directions *around the coils*. However, this is difficult to represent on these 2D diagrams without making them confusingly complicated - I'd need to use $\odot$ & $\oplus$ "out of page/into page" type notation for *i* and *v*. Moreover, even if I did that, then the direction of these symbols would depend on which direction the coils are wound around the core. Adding this extra complication would not result in any increase in the understanding of how it works. So in the interests of simplicity, I just opted for up/down.

I'm sure some of the cleverer students will be able to think of inconsistencies resulting from the up-down notation. The solution - ask him or her to re-write the above using into page/out of page notation as an extension exercise!