This presentation was originally created as a one hour lecture class. This is not intended to be a stand alone text book on basic brake systems. I have added verbiage to the notes pages in an attempt to make the information more useful as a basic starting point for the new brake engineer.

It is anticipated that going through this will generate as many questions as it answers.
Presented By:
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Topics To Be Presented

- The basic principles
- Hydraulic layouts
- Component function
- Brake balance
- Stopping distance
- Government requirements
- Customer requirements
The Basic Principles

- Kinetic energy = heat
- Newton is always right!
- F = ma
- When all else fails see point 2
The brake system converts the kinetic energy of the moving vehicle into heat.

The brake engineer has two challenges:

1. Create enough deceleration to stop the car as quickly as the driver wishes, without exceeding the drivers comfort level with regard to pedal effort or pedal travel..

2. Manage the resulting heat energy so as not to damage the brake system or the rest of the vehicle.
Energy Conversion

A vehicle weighing 1600 kg.
At 100 kph has kinetic energy of:

\[
\frac{MV^2}{2G} \quad \text{OR} \quad 618,272 \text{ N-M.}
\]

Stopping the car at .8G takes 3.54 Seconds
This is equal to 174 kilowatts (233 HP).

The equation for the energy conversion is very simple as you can see.

An interesting observation is that a typical car of this size has an engine with about 90-105 KW (120-140 HP). This means that the brakes have to deal with about twice the power of what the engine puts out.
Since the kinetic energy of a moving vehicle is a function of the square of the speed, the speed from which you wish to stop a vehicle is much more important than the mass of the vehicle.

When selecting a brake system the performance of the powertrain must be taken into consideration.
The Basic Equation

\[ F = ma \]

*The Brake engineer’s task!*
How do you calculate F?

I hope you have not forgotten your freshman physics.
This picture illustrates the force path from the driver's foot to the tire road interface.

- \( f \) is the force applied by the driver's foot
- \( R_p \) is the pedal lever ratio
- \( F_b \) is the booster assist force
- \( A_m \) is the area of the master cylinder
- \( A_w \) is the area of the front caliper piston
- \( \mu \) is the coefficient of friction of the lining
- \( r \) is the effective radius of the caliper
- \( R \) is the loaded radius of the tire.

The effort or force exerted on the brake pedal combined with the output of the booster and the diameter of the master cylinder pistons determines the pressure (psi) in a hydraulic brake system.

The smaller the master cylinder bore diameter is, the higher the pressure will be for a given force on the brake pedal. However, a smaller diameter master cylinder will require more travel of the piston to displace the same amount of fluid as a large piston.

The larger the diameter of the wheel cylinder or caliper piston is, the higher the force will be pushing on the brake shoes.

It can sometimes be very difficult to get accurate information about the caliper effective radius and/or the tire loaded radius.
There are two layouts of hydraulic brake systems used in cars and light trucks.

**Front/Rear hydraulic split:**
Also called axle by axle, vertical, and some times “black and white”.

**Diagonal Split:**
Also called criss-cross.

The type of split is only significant in the event of a hydraulic system failure.

Let's look at the hydraulic circuits used in modern passenger cars and light trucks.
Typically rear wheel drive cars and trucks have front/rear split systems. Front wheel drive cars almost always have diagonally split systems.

The front suspension design of front wheel drive vehicles, (small positive or a negative scrub radius) allows the use of diagonal split hydraulic systems.
This is a diagram of a basic front-rear split hydraulic system.

- Notice that there is one line from the master cylinder to the rear axle brakes and one line to the front axle brakes.
- You might also notice that the line to the front brakes comes from the “rear” outlet of the master cylinder, and the line to the rear brakes comes from the “front” outlet of the master cylinder. This can cause a lot of confusion when discussing brake systems.

The solution to this Semantic problem is to use the technically correct terms for describing master cylinder circuits.

The hydraulic circuit that is closest to the open end of the master cylinder (also closest to the power brake unit and the driver) is always referred to as the “primary” circuit. The circuit closest to the closed end of the master cylinder casting is always referred to as the “secondary” circuit. This nomenclature should be used regardless of how the hydraulic lines of a vehicle are connected to the rest of the brake system.
Since there is one line to each brake a diagonal split system requires more tubing and more connections than a front rear split system.

The distinction between front and rear hydraulic circuits or master cylinder outlets becomes meaningless also.
Diagonal split hydraulic systems are commonly used on front wheel drive vehicles. This is primarily because under unladen or driver only conditions there is so little weight on the rear axle that the vehicle would not be able to meet the legally required stopping distances with only the rear brakes.

Rear brake only stopping distance can be a problem with rear wheel drive pickup trucks also. They must use a front rear split because the front suspension design of these vehicles (large positive scrub radius) would produce unacceptable pull during a stop with a 1/2 system failure and a diagonally split hydraulic system.
Here is an overview of a typical passenger car brake system.

You can see the major components:

- The brake pedal
- The power brake booster
- The master cylinder
- The hydraulic control valve
- The hydraulic lines
- The front disc brakes
- The rear drum brakes
The braking system of a modern vehicle is usually divided into four sub-systems to make all the engineering a little more manageable.

During this tutorial I am going to cover the actuation and foundation sub-systems.

Parking brake systems and especially ABS/ESP systems would easily require entire separate sessions.

In order to understand the function of ABS/ESP systems a basic understanding of the foundation brake sub-system and the actuation sub-system are required in any case.
**Actuation Sub-system**

- Brake Pedal
- Power Brake Unit
- Master Cylinder
- Hydraulic Lines
- Proportioning Valves
The Brake Pedal

The brake pedal is a simple lever. The fulcrum is at the top of the pedal arm, the input is at the opposite end, and the output is somewhere in between. For example, a driver input force of 100 N is multiplied by a 4:1 ratio into 400 N of output force. This output force becomes the input force for the power brake unit or booster. The travel of the driver's foot will of course be 4 times the travel of the booster input pushrod.

Pedal ratios on most vehicles today vary between 3:1 and 5:1
Today there are almost no vehicles sold in any major market that do not have power assisted brakes.

Some systems use hydraulic or electro-hydraulic methods of power assist.

We will only discuss the vacuum power assist unit which is by far the most common.

Hydraulic Power brake units

Some cars have hydraulically operated (hydro-boost®) power brakes. They are used on large trucks and vehicle with diesel engines which of course have no natural engine vacuum.

The power steering pump which serves the car’s steering gear is also the power source for operating the hydro-boost unit and supplies fluid to the booster. Pressurized oil from the pump’s reservoir flows through an open center valve in the booster to an open center valve in the steering gear and returns to the pump.

No changes are needed in the pump or steering gear to accommodate the unit. Minor changes in the pump reservoir are required to allow for the expansion of the increased volume of oil in the system. A third line from the booster returns to the reservoir a small amount of oil due to the booster’s internal leakage as the brake pedal is applied.
Unapplied Condition

In the released position the vacuum control valve is open and the atmosphere control valve is closed.

The unit is said to be “vacuum suspended”.

Since there is equal vacuum levels on both sides of the diaphragm no force is produced.

The booster or power brake unit is a force amplifier

- A power brake unit cannot significantly affect pedal travel.
- The amount of assist available is directly proportional to the amount of vacuum available.
- All modern vacuum boosters have a direct mechanical push through feature in the event of a loss of the power assist function.
- The amount of pedal force required to stop a power brake vehicle without the power unit is very high.
**Applied Condition**

In the applied condition, the vacuum valve is closed and the atmospheric valve is partially opened allowing atmosphere to enter.

The resulting pressure differential across the diaphragm generates the boost force.

**Full Applied**

When the booster is in full applied position, full atmospheric pressure is applied to the back side of the diaphragm and the maximum pressure differential is obtained. This is referred to as the "**vacuum runout**" point of the booster and may be felt as a definite "hardening" of the pedal. Any additional output is obtained by increased operator effort on the brake pedal without power assist from the booster. When runout is reached most drivers think the "pedal is on the floor".

A check valve between the engine intake manifold and the booster retains sufficient vacuum in the booster to provide some assist after the engine stops running. The booster can then deliver enough output for several moderate brake applications. Beyond this point, braking effort becomes very high.
This is a typical force in force out performance curve for a vacuum booster.

This curve is taken from SAE Standard J1808.

Detailed definitions of each of each part of this curve can be found in the standard. Any discussion about vacuum booster requires that all parties use the same definitions for these various parts of the performance curve.
The master cylinder converts the input force (output from the booster) into hydraulic pressure.

Master cylinders in cars prior to 1967 contained a single piston. Reserve fluid in these early models was stored in the master cylinder’s single reservoir. Braking force was transmitted directly to each of the four wheel cylinders.

All passenger cars sold in the U.S. after January 1, 1967 employ dual master cylinders. All current brake systems use two pistons in tandem. One piston serves one half of the brake systems and one piston independently serves the other half. Added safety was the principal reason for changing to dual master cylinders. With the dual design, when there is a failure in either of the two hydraulic systems, the remaining system can still stop the car when force is applied at the brake pedal.
When the brake pedal is in the released position, both pistons in a dual master cylinder are retracted. Each piston has fluid in front of it and both compensating ports are open to the fluid reservoir. Since the fluid reservoir is “vented” to atmosphere, the fluid in the master cylinder and throughout the brake system is at atmospheric pressure.

The fluid will stay at atmospheric pressure regardless of expansion or contraction resulting from temperature changes in the brake system.
Depressing the brake pedal causes the primary piston to move forward. When the primary piston moves forward, it blocks off the primary compensating port and seals the fluid in front of it. At the same time, the primary piston return spring (which has a higher installed load than the secondary piston return spring) moves the secondary piston forward and causes it to close the secondary compensating port. As pressure builds up in the secondary system it allows the primary system return spring to compress and generate pressure in the primary system also.

When the brake pedal is released, the master cylinder's springs retract the pistons quickly. However, the fluid in the wheel brakes returns to the master cylinder more slowly and a small vacuum is generated in the master cylinder bore. Atmospheric pressure on the reservoir fluid pushes the fluid through the filler ports, past the cups, to equalize pressure in the piston chambers.
Primary System Failure

Loss of brake fluid through leaks or broken brake lines can be a cause of brake failure. If the failure occurs in the primary system, pedal movement causes the unrestricted primary piston to bottom against the secondary piston. Continued movement of the pedal moves the secondary piston mechanically to displace fluid and transmit pressure to actuate the brakes connected to the secondary system. The pedal travel will increase by a large amount. To activate the secondary system the brake pedal must be pushed well past the position for normal braking. Pumping the pedal will do no good and will not activate the second hydraulic system.
If there is a failure in the secondary system a similar series of events occurs. Initial pedal movement, in this case, causes the unrestricted secondary piston to bottom against the forward wall of the master cylinder. Movement of the primary piston displaces fluid and transmits hydraulic pressure to actuate the brakes connected to the primary system.

Again the pedal travel will increase by a large amount. To activate the remaining system the brake pedal must be pushed well past the position for normal braking to "bottom the failed circuits piston. Pumping the pedal will do no good and will not activate the remaining good hydraulic system.
The Fixed Proportioning Valve

A fixed proportioning valve reduces the pressure increase to the rear brakes above a predetermined pressure called the “split point”. The rate of pressure reduction is called the proportioning valve “slope”. The valve must be located between the master cylinder and the rear brakes.

Proportioning valve:

The proportioning valve balances front-to-rear braking action during high deceleration stops and prevents premature locking of the rear wheels.

Almost all non ABS equipped vehicles have some type of mechanical proportioning valve.

When ABS was first introduced and for many years thereafter vehicles with ABS also had mechanical proportioning valves.

Today most ABS equipped vehicles provide for the proportioning function by using the computer and electronically controlled valves in the ABS units. This is called **EVBP** (Electronic Variable Brake Proportioning)
Fixed Proportioning valve

A fixed proportioning valve reduces the pressure increase to the rear brakes above a pre-determined pressure called the "split point." The rate of pressure reduction is called the prop valve "slope." The valve must be located between the master cylinder and the rear brakes.

Typical slope values are: 0.27, 0.34, 0.43, and 0.59. Split points usually run between 17 bar (250 psi) and 35 bar (500 psi). Higher values of split point are available.
Foundation Brake Sub-system

- Disc Brakes
- Drums Brakes
- Linings
A typical disc brake corner has a caliper and a rotor. The rotor turns with the wheel and the caliper is fastened to the suspension.

Most of the energy that is converted into heat goes into the rotor.

One of the key factors in selecting the correct size brake system for a given application is to balance the thermal mass and surface area of the rotors with the amount of energy that they are going to have to handle.

Increasing thermal mass, by making the rotor thicker and/or larger in diameter, will reduce the temperature rise that results from a given energy input. This most directly affects the peak temperatures at the end of a fade sequence.

Increasing the surface area of a rotor, by making it larger in diameter and/or adding more fins will reduce the steady state temperature that it reaches during prolonged braking such as a long mountain descent or long periods of stop and go driving. Increasing the diameter is much more effective than changing the fin configuration.
A typical brake caliper can be thought of as nothing more than a hydraulic C-clamp.

The diagram shows the brake fluid pressure pushing the piston to the left which pushes the inboard shoe and lining against the rotor. At the same time the caliper housing moves to the right and pushes the outboard shoe and lining against the other side of the rotor to create a clamping force. This is where the “2” in the system equation comes from. (remember every action has an equal and opposite reaction)

In order to calculate the amount of clamping force generated in the caliper, the incoming pressure is multiplied by the area of the caliper piston. As an example, 40 bar (580 psi) into the caliper would push against the back of a 57mm piston. This pressure is also pushing the back of the caliper bore in the other direction with an equal force. Therefore the total clamp force on the rotor will be equal to two times the area of the 57mm piston. Working the numbers reveals that 40 bar will generate 20,416 Newton's (4640 lbs..) of clamp force (40 bar x 25.52 cm² x 2).

The two linings rub on the rotor which is turning with the wheel. The friction produces torque which slows the wheel.
This is a typical drum brake assembly.
At the macro level a drum brake works like a disc brake. You put hydraulic pressure in and get torque out.
The linings on the shoes rub against the drum and produce torque that slows the drum and the wheel.
The major differences have to do with the governing equation for calculating the amount of torque generated by a given amount of pressure. In drum brakes you cannot use; 2 X the lining $\mu$ X the piston area X the effective radius. You must substitute a number called the “brake factor” The “brake factor” replaces “2 X $\mu$”.
The brake factor for a drum brake is a combination of the geometry of the brake and the coefficient of friction of the linings. The relationship between the brake factor and the lining coefficient is not linear. Brake factors for the wide variety of drum brake designs range from approximately 2 to about 6.

The detailed understanding of drum brakes is a course by itself.
Drum Brake Wheel Cylinder

There are two pistons inside a typical wheel cylinder that move outward with pressure. They push the two shoes out against the drum which is rotating with the wheel.

The cup expanders and the small spring keep the cup seals against the walls of the wheel cylinder during the evacuation and fill process in assembly plants. They also ensure that air is not drawn into the system during a quick release of the brake pedal in cold weather when a vacuum can be created in the wheel cylinder.
Brake Linings

- Brake linings are probably the least understood part of a brake system.
- The output of any brake is directly related to the coefficient of friction (µ) between the lining and the disc or drum.
- The challenge is knowing what the instantaneous value of µ is during any given stop.
- Any design calculations you do, go right out the window if the actual value of µ is not the same value you assumed.

♦ As you have seen in the tutorial on brake testing, there are many different methods for measuring µ. The trick is to use the method that gives you a µ value that is the same as you would get during an actual stop in the vehicle.

♦ We all talk about lining µ but we really mean the effective coefficient of the “friction couple” between the lining and rotor or drum surfaces. Any change in either of these parts can and will affect the resulting friction.

♦ Changing the machining finish on a rotor from ground to turned could result in a different effective friction value for many hundreds of stops.

♦ The instantaneous value of µ changes during a single stop.

♦ When you compare linings you must use the same dyno test and the same sections of the test. It also means that you cannot only look at average values for a whole stop but must look at the “in-stop” data.
**Brake Linings**

Remember the equation for a disc brake

\[ F \propto \frac{r}{R} \times 2 \times \mu \times \frac{A_W}{A_m} \times (R_p \times f + F_b) \]

The tutorial on brake testing covers some information about how to extract values of \( \mu \) from dynamometer test data.

Without the “correct” value of \( \mu \) you can’t do any meaningful brake system design calculations.
Brake balance is the science of the relationship between the vertical forces on the front and rear tires and the torque applied by the front and rear brakes at any given instant.

The first question you may ask is what difference does it make? and why should I care??

To answer this lets look at what happens to a vehicle when the wheels at one end of a vehicle lock before those at the other end.
Both Front Wheels Locked:

- You can’t steer
- The vehicle goes straight
- OK, if you must hit something
- Not good if you are on a curved road

The occupant protection and crash energy management features of a typical vehicle are optimized for a frontal impact. In many instances therefore, it maybe better to hit something head on, if you can’t avoid the impact, than to hit something with the vehicle sideways.
We have all been told at one time or another; "steer in the direction of the skid." What we should have been told is; "steer in the direction that the rear of the car is skidding".

In the real world if a vehicle has both rear wheels locked at a relatively high speed, the rear end will come around at such a rapid rate that most people may not be able to maintain control.

If you watch auto racing, you may observe that when a professional driver starts to lose the back end of the vehicle they will lock up all four wheels and just ride it out.

They do this because if you release the brakes when the vehicle is skidding it will most likely fly off in whatever direction the front wheels are pointing.
Front Lock

If there is more front brake torque than dynamic front weight

Brake torque distribution

Dynamic weight distribution

20% 80% 30% 70%

The front wheels will lock up before the rears
Rear Lock

If there is more rear brake torque than dynamic rear weight;

Brake torque distribution

30% 70%

Dynamic weight distribution

20% 80%

The rear wheels will lock up before the fronts
Optimum braking is achieved when brake torque distribution matches dynamic weight distribution.

You can calculate the dynamic weight distribution of a vehicle for any given deceleration;
Vehicle Loading Variation

Brake system balance must also deal with the variation in vehicle weight distribution under different loading conditions.

Driver Only

35% 65%

Fully Loaded (GVW)

60% 40%

• For most vehicles the static weight distribution changes significantly between empty and fully loaded conditions.

• When designing a brake system you have to consider this variation as well as the changes in dynamic weight due to different decelerations.

• Obviously a fixed proportioning valve has no ability to deal with the changes in static front to rear weight distribution. This is why ABS and electronic proportioning is becoming more and more common.

• Remember that if the coefficient of friction of either the front or rear lining is changed all of your calculations for brake balance change. Some brake linings have significantly different mu levels at different temperatures which can really complicate your life.
Calculating Dynamic Weight Transfer

\[ W_{df} = \frac{W_t \times H_{tcg}}{W_b} \times D + W_{fs} \]

- \( W_{df} \) = Front dynamic weight
- \( W_t \) = Total vehicle weight (mass)
- \( H_{tcg} \) = Height of the center of gravity
- \( W_b \) = The wheelbase
- \( D \) = Deceleration
- \( W_{fs} \) = Static front weight

The dynamic weight shift can be calculated by taking the sum of the moments about the front tire to road contact point.

As you can see from this equation the total front dynamic weight \( W_{df} \) is equal to the front static weight \( W_{fs} \) plus the product of the total vehicle weight \( W_t \) times the height of the C.G. \( (H_{tcg}) \) divided by the wheelbase \( (W_b) \) and multiplied by the deceleration \( (D) \). Then, of course, the dynamic rear weight is just the total vehicle weight minus the front dynamic weight.

Now all you have to do is design a brake system that has a front to rear torque distribution that changes with vehicle deceleration.

The proportioning valve reduces the pressure to the rear brakes above a certain pressure to partially compensate for the dynamic weight shift.

Naturally there will be more deceleration at higher pressures since the total torque of the front and rear brakes will be higher and the mass of the vehicle has not changed. This brings us back to go old \( F=MA \).
Using the weight transfer equation you can easily calculate the normal forces on the front and rear tires for any deceleration.

Then multiplying by the tire to road coefficient of friction and the radius of the tire, you can calculate the front and rear brake torque required for perfect balance.

If you do this for light and fully loaded vehicles over the whole range of decelerations, you will get curves that look like this.
Once you know what the ideal front and rear torques are you can calculate the required front and rear brake pressures by working the brake torque equations for the front and rear brakes backwards starting with the torque and solving for pressure.

In the real world this is were things can get tricky. If you use a nice simple linear model for the front and rear brakes all this is straight forward. If the rear brake is a drum and/or you have a lining whose $\mu$ varies with pressure and/or speed calculating the actual required front and rear pressure gets a lot more complicated.

When a test vehicle does not perform according to the calculations it is usually because the actual lining to rotor or drum friction values where not what you thought they were.
### Stopping Distance

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<th>Does not Depend on:</th>
<th>Does Depend on:</th>
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<tr>
<td>• Type of brakes</td>
<td>• Vehicle balance</td>
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<tr>
<td>(Disc vs Drum)</td>
<td>• Skill of driver</td>
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<td>• Size of brakes</td>
<td>• Measuring method</td>
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<td>(Assuming you have</td>
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<td>enough torque to</td>
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<td>skid the tires)</td>
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**Vehicle balance:**

Since the highest deceleration is achieved when all four wheels are just about to skid, stopping distance is critically dependant on front to rear balance.

**Driver Skill**

Driver skill effects stopping distance because in a non-ABS vehicle the test driver must obtain the highest possible decel without locking any wheels. For a given vehicle balance the better driver will always get the shortest distance. This indirectly explains one of the biggest benefits of ABS. Under emergency braking conditions ABS allows almost everyone to match the braking skill of a professional driver.

**Measuring Method:**

How you measuring stopping distance has an effect on the numbers you get. According to the procedures in MVSS-135 and ECE-13, stopping distance is measured starting from the initial application of force to the brake pedal. For the vast majority of vehicles this means that the measuring systems are triggered off the stop lamp switch circuit.

Some magazines use a device that starts to measure when vehicle deceleration is detected. The difference between these two methods can be 20-30 feet at 60 mph.
There is an old brake engineer’s saying:

**The brakes stop the wheels but the tires stop the car.**

This chart shows that different tires on the same vehicle can have an effect on stopping distance.

Take note that the tires with the shortest dry surface stopping distance (the Michelin) do not have the shortest wet road stopping distance (Continental). Like almost everything else in engineering tire traction is a compromise.
**Brake Fade**

Brake fade is the loss of performance resulting from the lining friction decreasing as the lining and rotor or drum rises in temperature.

When linings get hot they not only change in friction value but they also usually increase in compressibility. As a result during a series of hard stops when brake temperatures increase there will be an increase in the amount of fluid required to reach a given pressure as well as an increase in the amount of pressure required to produce a given torque.

Dynamometer testing is a very good way of measuring the fade performance of linings.

After you have dyno fade data you need to plug the information back into the basic equations we have talked about to see what that means to the whole vehicle.

Remember to check front to rear balance.

Disc brakes are less susceptible to fade than drum brakes. This is one of the reasons that drum brakes are no longer used on the front of road vehicles.
All light vehicles sold in the United States for the 2003 MY must meet MVSS-135.

Front to rear balance is important and lining $\mu$ is critical.

Because there is a requirement to stop the vehicle at fully rated load (GVW) with no power assist, if the linings on the vehicle the government selects to test have a significantly lower friction level than those that were used during the design and development process, the vehicle may not certify.

Vehicles sold in the European Economic Community (EEC) must meet ECE-13.

These two standards are similar but not identical. If you sell in both markets you need to run both tests.
All the OEMs and major brake and lining suppliers know what the customer wants:
Brake that last forever
Brakes that make no noise
Brake that cause no vibration or roughness
Brakes that never fade
Brakes with good pedal feel
and brakes that do not add significant cost or weight to the vehicle.

As soon as you come up with one of these systems please give me a call.
Although we talk a lot about world cars and a global economy, the fact remains that customers in different parts of the world have different priorities when it comes to their brake systems.

Failure to make the correct trade-off’s for a particular region of the world will lead to high warranty, customer complaints, bad write ups in auto magazines, and lost repeat sales.
Any Questions?