The Open Differential

That's more or less the diagram of the inside of differential for a rear wheel drive car. A front wheel drive car basically doesn't have a normal "Input Shaft", but everything else is the same. I simplified it greatly as there may be more than 2 spider gears and I didn't show the bearings where the output shafts go through the housing. A real differential is also very compact with all the gears nearly the same size and packed together. Additionally, all perpendicular gear intersections use beveled gears (cut at an angle) but that was too hard to draw.
See the diagram of a center differential.

(The part of the left is the differential part on right is a Viscous Coupling)

Anyway, I'll explain and you can look at the diagram. (Click on the image to open in a new window)

The left and right drive gears have teeth on their sides. They are attached directly to the end of the left and right output shafts, and turn freely on bearings in the ends of what I called the Outside Housing.
The thing labeled “Outside Ring Gear” is a ring gear attached directly to the housing which takes power from the input shaft which comes from the engine (directly or via drive shaft). When the input shaft turns, the ring gear turns and the entire differential housing turns. But I'm getting ahead of myself. Let's see what the differential does all by itself.

**Example 1:**

So you're holding this thing in your hand by the outside housing. If you grab the right side output shaft and turn it, it'll turn the right drive gear. The drive gear will spin the spider gears, the spider gears will turn the left drive gear and the left output shaft on the opposite side spins in the reverse direction.

That is the "open" part of an open differential.

So how is power applied?

**Example 2:**

When torque is applied to the input shaft, it turns the entire housing as I've said. The housing is attached to the axles of the spider gears. I have to repeat that. It's attached to the axles of the spider gears, so it's pushing the spider gears sideways such that the spider gears are forced to move around and around (actually end over end... whatever makes sense to visualize). If the resistance on both output shafts is the same, then the spider gears do *not* themselves rotate as they did above. They simply remain fixed to the side of the housing, and push equally on the teeth of both drive gears, and both drive gears turn at the same speed.

**Example 3:**

Ok, now grab the right output shaft and hold it fixed. Continue to rotate the input shaft. The outside housing continues to rotate at the same speed, as it did for Example 2. However, now the spider gears can't make both output shafts turn at the same speed (as one is being held stopped).

Here's where you need a hands on demo of what happens.

**Wacky Demo 1:**

Grab a computer or audio CD. Stick your finger through the hole in the middle and roll it slowly across a table or desk. While you're doing that let the fingers on your other hand rest gently on the top edge of the disc, and move with it. The disc represents the spider gear. Your finger is the axle attached to the housing moving at a fixed speed. The table represents the non-moving right side drive gear, and your other hand is the left side drive gear. Note that as you roll the disc at a constant speed X, the top edge of the disc is moving forward at speed 2X.

That's what happens inside the differential too. If you hold one side fixed, and continue to apply torque, the other side of the differential rotates at twice the speed it normally would (twice the speed of the ring gear and housing).

When you're driving around a turn, this all works together. The inside tire must turn slower than the outside. With constant throttle the housing speed remains fixed, but the spider gears turn very slowly which allows the wheel on the inside of the turn to rotate a little slower than it normally would and the wheel on the outside of the turn to rotate faster than it normally would. The housing rotational speed is always the average of the two sides. Great for going around turns at slow speeds.

**So what's wrong with the open diff?**
The problem is an open diff always tries to balance the torque. That's a hard statement to get a grasp on, but it means that if the spider gears are pushing on both drive gears and one of them offers lots of resistance (tire sitting on pavement) and the other side offers no resistance (up in the air, or sitting on a patch of ice), then it will find a happy balance where both sides are receiving almost no torque at all. All the rotational energy is guided to the side with the least resistance. In the end, that side spins very fast and the pressure on each drive gear is the same. Almost no torque is needed to spin one wheel, and therefore almost no torque is going to the other side as well. Anyone who's driven on snow or ice knows this trick.

Now back to the original question. **What's a limited slip diff?**

Let's start with the opposite of the open diff first.

**The Locking Differential:**

Go back to the diagram. Look at the spot where the line from the label "Right Drive Gear" touches the drive gear.

Drill a hole there all the way through it, and through the left drive gear on the other side. Stick a steel pin through the holes. Now both sides of the differential are locked together. This is a simplified "locking differential". The housing turns, the spider gear pushes on both drive gears, and no matter what they are forced to turn at the same speed. Real locking diffs use a pneumatically or hydraulically activated sleeve that slides across between the drive gears out near their edge to lock the drive gears or spider gears in place, but the effect is the same. This is great when you have no traction on one side, because no matter what, both sides turn at the same speed, and if one side offers lots of resistance, and the other none, then effectively all the "usable" or "useful" torque goes to the side where there is resistance. It's getting 100% of the available torque. The side with no traction doesn't need torque to spin helplessly, so it's not really getting 50% of the torque as you might think.

Problem with a locking diff, is of course why we don't all just have solid axles. When you go to drive around a corner, both tires are forced to turn the same speed. Either one drags while the other spins a little, or probably the outside matches the ground speed (as the weight transfers) and the inside tire spins on the pavement (shorter distance to travel, but it's spinning as fast as the outside tire which has farther to go in the same time). Either way it tends to make the vehicle want to go straight all the time.

**Limited slip differentials.**

A limited slip differential is a compromise. We'd like a full locking diff in specific instances of extreme traction imbalance but otherwise would prefer operation closer to an open diff, so that the tires can turn at different speeds around corners.

**Disclaimer:** I'm making up some of the implementation details below to illustrate a concept. The real construction details of these devices are most certainly different. My intent is to allow you to visualize how a limited slip diff differs from an open or locking diff. Some of the designs I've heard, of but don't know where or if it's been implemented.

**Viscous Coupling: (Syncro)**
Checkout the diagram above and put some intermeshing fins in the space between, and attached to, the drive gears. Make the fins all move close to each other, but let them pass without touching so both drive gears can still rotate at different speeds. Now enclose the space around the fins and fill it all up with a thick fluid. Now as long as both sides are turning the same speed the fins also move at the same speed and the difference between their speeds is zero. But go back to Example 3 where one side is held still. As you rotate the housing at speed X, the difference in speed between left and right sides is 2X. That's enough to get the fins all moving past each other through the oil and the fins of one side impart some energy to those on the other side via the liquid, which typically is designed to heat up and become more viscous in this situation. Now some percentage of torque is transferred to the right side that you're trying to hold still.

This is a speed sensitive limited slip. If you turn it very slowly very little torque is transferred to the fixed side. As the input speed increases, it becomes harder and harder to hold the right output shaft still. As the speed difference increases, so does the torque transferred. Eventually enough torque will transfer through the viscous coupling to get your car out of whatever predicament it's in.

The downside is that you're constantly turning all these fins and liquid and if you're driving around tight corners a lot, it is transferring torque across to the other side, perhaps when it doesn't need it. You may still get some wheel spin on the tire on the inside of a turn, for instance. Also, you may find, after getting stuck that the side that's spinning ends up spinning so much that the tire digs a hole in the ground out of which you can't climb, even when torque is transferred over to the side with traction.

A VC diff is rarely used at the axles.

The VC is most often used as, or part of, the center differential in an AWD system. The VW Syncro system was originally developed by Audi and then discarded in favor of a torsen diff, but VW incorporated the viscous coupling into their Syncro AWD system. That has since been replaced by the 4motion system. Some AWD systems simply put a VC in the center of the car and nothing else. When the VC is tied to a differential, then the power is normally split between front and rear...
axles equally. Without the differential and only the VC then power normally goes to only one end of the car and the other end just floats along with the VC absorbing any speed differences. If it's normally a front wheel drive car, and the front wheels start to spin, then the pure VC starts transferring torque to the rear wheels. Others, like Porsche and Lamborghini, have done it the other way around, transferring torque to the front only when the rear tires slip. You'll see these described with something like a 90/10 torque split because they design them to always slip a little bit even when driving straight so that the VC will activate quicker.

One big problem is that VC interferes with the operation of the ABS brakes. The VC keeps the wheel speeds linked together, while the ABS may need to brake one side (or end) of the car harder than the other. The VC may cause a tire to slide while the ABS is trying to prevent it from sliding. Most VC AWD systems have some sort of disengage mechanism that takes the VC out of commission as soon as you step on the brakes.

Clutches (Passive, Hydraulic, and Electronic):

Most of the more popular LSD systems fall into this category. I'll just get this out of the way up front. The biggest problem with all clutch systems is that they wear out over time.

Anyway, how do we get rid of all those fins, liquid, and weight from the VC?

Passive Clutch:

Let's try a passive clutch. To the back of one drive gear is attached a set of metal clutch plates, and to the outside housing are clutch pads. Back this clutch pack with heavy springs that squeeze the plates between the clutch pads and so on. Again, nothing happens in normal conditions with equal traction, as both drive gears turn at the same speed. When one side loses traction and the diff tries to spin that side, the clutch simply imparts a fixed amount of torque back to the other side. With a passive clutch, it doesn't get better with speed either. If anything it transfers less torque at higher differential speeds, (dynamic versus static friction). You might be tempted to add bigger springs to make the clutch engage harder but then you'll end up with some of the same bad traits of a locking diff under low traction conditions when just driving around corners at normal speeds when one side will drag and the other spin.

Progressive/Locking Clutch (Positraction or Salisbury type):

This is probably the most common type of LSD. Here there are a set of clutch plates attached to the inside of the housing just outside of each drive gear, and a set of clutch disks attached to the output shafts, but also still inside the housing. There are two thick pressure rings which attach to the inside of the housing near the spider gear shafts. The pressure rings push outwards against the clutch packs. The space between the pressure rings forms an opening that is wedge shaped, and the spider gear shafts themselves, form the wedge. As power is applied to the ring gear, and transmitted to the housing, and down into the pressure rings, they start to push on the spider gear shaft which (depending on traction conditions) wedges itself toward the end of the opening between pressure rings, which forces them away from each other, which applies pressure to the clutch packs, which locks both drive gears to the outside housing and under very high power the differential locks up nearly solid.

So this one is **power sensitive**. Note: there must also be some preload built in, for use in low traction conditions. This system relies on there being some resistance to the applied power to cause the pinion gear (spider gear) shaft to wedge open the pressure rings. If you started with no static clutch pressure, then under very low traction conditions (one side on ice), there won't be enough resistance to wedge the pinion shaft in place and it'll remain an open diff. As a result there's usually enough static load added to provide some constant torque split to both sides, and then if you hit the gas, it'll lock up the diff and you get torque down to whichever side can use it.
Simple Hydraulic Clutch:

Put the same clutch pack in, but put a hydraulic actuator behind it instead of the springs. Now, pumping oil into the innards of a rotating mechanism is possible (and I'm sure has been done) but is hard so instead it's often done in a clever fashion. You attach a small hydraulic pump to one or more of the spider gears, or a floating gear that spins at the same speed as the spiders but without carrying the load. The pumps simply scavenge the oil from wherever they can inside the case and pump it into the actuators behind the clutch. Remember the spider gears only rotate when the drive gears are rotating at different speeds. As you can guess, this system is also speed sensitive as the hydraulic pump only works when one side is spinning faster than the other, but the hydraulics offer much quicker activation than the viscous coupling from above, and the clutch pressure can be maintained with less speed differential. We may still have the clutch wear problem. Also the activation rate is basically fixed by the designers.

Electronic Clutch (or electronically activated hydraulic clutch):

Getting electricity into the center of the diff isn't much easier than getting hydraulic fluid in, but it's possible. So electronic actuators may put inside to either directly drive the clutch, or to run an electric hydraulic pump, or simply to regulate the rate of the hydraulic pump in the previous system. Alternately, it usually just uses an electronically activated hydraulic pump outside the housing but inside the transaxle (or differential case) that pumps oil to a hydraulic actuator that pushes against a sliding ring around one or both of the output shafts which ultimately reaches through holes into the clutch pack. In this configuration one can apply a large amount of pressure to the clutch pack inside the diff. The nice thing about this system is that it's infinitely tunable. You can lock the clutch up at any speed to transfer from 0% to 100% of the torque to the side that can use it most. The new 4motion system uses electronically activated hydraulic bypass valves, and from I hear can be tuned via software to put the power anywhere. Basically it's a simple hydraulic system as above, but the pressure can be regulated via electronically controlled valves. The old Mercedes 4matic system used electronically activated hydraulic clutches first at the center diff, and then later at the rear diff dependent on wheel speed measurements taken from the ABS wheel speed sensors. These systems are often fairly complex as they require a computer to keep track of it all, and they must usually apply pressure to the clutch pack in the differential via sliding bearings. Those bearings are at risk of increased wear along with the normal clutch wear. The most complex system ever developed was that on the Porsche 959 which didn't even wait for wheel slip before transferring torque. It monitored everything... steering angle, lateral acceleration, throttle position, yaw rate, and wheel spin, to constantly shift the torque where required. The ultimate goal was to cure the rear engine RWD tendency to lift throttle overseer that the 911 suffered until 1993. (They eventually fixed the overseer problem with simply a new rear suspension and fatter tires.)

Side Note: I should also mention the Centrifugal Clutch as it's like the hydraulic clutch, but it uses weights and mechanical linkage instead to engage the clutch when the housing spins fast. It's simple, but speed sensitive and requires a lot of spin to make it engage.

EDL (often referred to as Electronic Traction Control.)

This system is used by the VW GTI-VR6 (FWD) and Mercedes ML320 (AWD) and probably others. It's the poor man's LSD. (Some people dislike my characterization of it, as it can be very finely tuned, but it's still very cheap to implement and has some reliability problems.) This is an electronically regulated speed sensitive system using the two independent ABS channels. Start with an open differential and go back to Example 3. You're holding onto the right output shaft while the input shaft turns. Now add a disc brake and rotor on the left input shaft. Engage EDL. When the computer senses a speed imbalance between left and right, (remember the left shaft is spinning at 2X and the right is not moving at all), it simply applies the brakes to the left side output shaft. The open differential immediately tries to balance the torque. You will feel it trying to turn the right side immediately. If it can grab the left harder than you're holding the right (which it most
certainly can and will) then it'll immediately transfer some rotation to the right output shaft and it will twist out of your hand. If you could hold onto the right side hard enough (weld it the side of a tractor trailer truck), it would be forced to slip the left brake disc, or stall the engine.

In practice, the engine will not stall because the maximum resistance is simply whatever it takes to move the mass of the car, or spin the other tire. So if one side is spinning and the other side has traction, then the EDL will slow the spinning side, and the torque transfers to the side with greater traction and either that side spins or the car moves.

Now, all my examples have been pretty extreme. The EDL doesn't actually stop anything. It simply slows it down until the speed difference is equalized, and it does this by pulsing the ABS channels maybe a dozen times a second. It switches off when the speed differential is low enough.

Also note it does not try to prevent wheel spin! If both sides lose traction at the same time and spin at the same speed then EDL has no idea anything is wrong. A more advanced system measures the difference between the speeds of all 4 wheels during acceleration and assumes that anything spinning faster than the slowest rotating wheel is slipping. A cheap system will apply the brakes. An expensive system will reduce the throttle until the problem goes away. BMW's and new VW's use this method to prevent wheel spin.

The problem with the way EDL works is that it's pretty harsh. The pulsing of the ABS isn't progressive. If the ABS is on, it applies full braking power followed by zero braking power... full, zero, full, zero... The torque from the engine that's being transferred repeatedly all the way across the drivetrain from wheel to wheel a dozen times a second puts stress on everything. Brakes, rotors, axles, U joints, output shafts, and the differential itself. The left and right halves of the differential in the VW 02A transmission are held together with rivets which if forced to take this pounding too long will eventually fail.

Did I mention EDL uses the brakes? Perhaps "uses up the brakes" would be more appropriate. It's really designed for emergency low traction situations and not drag racing or rallying or other long duration, low traction situations.

**So why use EDL if it's so bad?**

Well, the torque transfer is only really bad if the input torque is high and the resistance at the side where it's being transferred to is high. Such as... When you're spinning one tire on the pavement and the engine is cranking out 175 ft/lbs of torque. When it kicks that torque across from one side to the other, it finds that the other side (also on pavement) initially has lots of traction and therefore a lot of resistance which means that the drivetrain takes the brunt of the stress all at once. Worse case is when the side that is slowed, slows enough to regain full traction, while the other side starts spinning. Then the EDL compensates and brakes that side and the whole process repeats back and forth many times. Solution: take your foot off the gas.

On the other hand, if one tire is on snow, and the other is spinning on ice and the EDL has you accelerating slowly, the engine is producing little torque and if you tried to gas it hard, the torque transfer from the EDL meets up with little resistance on the snow so the torque "escapes" as wheel spin on the snow side. If it's ice and pavement then yes, you want to avoid mashing on the gas, but pulling away smoothly shouldn't present a problem as each pulse of the ABS transfers into a small bit more acceleration of the car.

**Should I worry when the EDL kicks in?** The ABS and diff can't transfer any more torque through the drivetrain than the engine supplies and the best case traction resistance allows. If traction is low on both sides, and power is high the traction is the limiting factor to how much drivetrain stress is induced. Otherwise, if one side had good traction on only one side, then just don't hammer the gas. If you're spinning the tires on dry pavement, expect TFS. Simple.

**Quattro and Quaife: (Torsen Differentials)**
Audi’s Quattro and the popular aftermarket Quaife systems use a set of worm gears inside the differential in place of the spider gears, which bind up when there's a resistive torque imbalance. That means, as long as both sides show equal resistance then they are free to rotate at different speeds, such as when going around a turn.

The whole thing is called a "Torsen" system as in "Torque Sensing" because it instantly reacts to torque imbalance transferring power to the wheels that can use it most. There's a difference between the two main torsen diffs. Quattro used something developed by Gleason called invex gearing which is really all about worm gears. A torque imbalance causes it to "try" to turn the low traction output shaft faster than the higher traction side, but that would cause the invex spider gears to turn, and they drive worm gears which have a greater mechanical advantage (due to the angle of the teeth) than the output sun gears have on the worm gears. That means that a multiple of the torque that would have gone to the low traction side actually goes to the high traction side.

So if 20 ft-lbs of traction is at the low traction side, something like 80 ft-lbs goes to the side that can actually use it. A ratio of 4 to 1 or 5 to 1 is common but changing the gear teeth angles changes the ratio. The Quaife uses helical gears to accomplish exactly the same thing, but the actual operation is not nearly as easy to understand.

Somehow the helical gears float in pockets on the inside of the housing and apply radial and axial forces generated by the angle of the gear teeth. It can be tuned just like the invex gears to vary the torque ratio.

Note however that without significant preload either torsen diff will not work well with a wheel completely off the ground. 0 ft-lbs time 4 is still 0. A simple braking trick helps though. (Note, the EDL system discussed above, actually works pretty well with a torsen diff. It activates rarely, but allows for much greater torque transfer when it does.)

It is capable of going from an open differential to say 60% locked differential condition absolutely instantly (zero lag), so many would argue that it's about as close to perfect as it gets for performance driving. There are no clutches to wear out. Several AWD systems like the Quattro system put a torsen diff in the center of the car to control slip between front and rear wheels. This system does not have the problem the VC does with the ABS. A torsen diff only distributes torque when it's under load. When it's freewheeling all the wheels can turn at different speeds as the ABS may desire. (Note: It looks like the current Audi Quattro system only uses the torsen diff in the center, and some other LSD or EDL at the axles.)

The disadvantages are that the mechanism is a bit heavier, more mechanically complicated thus expensive, and can't be tuned or adjusted dynamically. Plus, it reacts so fast and is so even handed that it literally makes a torsen diff equipped AWD car boring when you'd really like to hang it all out. If you want to go 100mph in the snow nothing beats Quattro. If you want to slide sideways or spin and recover, forget it. I've heard that VW's new 4motion system is much more fun because of its electronic control.

BTW, I do think that a Torsen Differential in a front wheel drive car is a good thing. If you plan on putting a blower on your engine, get a Quaife. If you want to drag race, get a Quaife. If you worry about EDL hammering and TFS a lot, get a Quaife. It'll help you put down power on a twisty road, and reduces torque steer.

So there it is.