

**CMOS Analog VLSI Design**  
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**Lecture – 01**  
**Introduction to CMOS Analog VLSI Design**

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## **CMOS Analog VLSI Design**

**Course Objectives:** Course deals with Basic theory of Analog Circuits, Design principles and techniques for analog IC's blocks implemented in CMOS technology. Although analog design appears to be much less systematic than digital one. This course will try to get some idea of good design principles to simplify process.



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The course objective of course, is that course deals with basic theory of analog. Already second year analog circuit course must have been done. So, nothing great will happen from there, basic things cannot change however, from there how do we design a chip? That is the course is trying to. But unfortunately, the word design itself says, that it has to be it is not available. That is why you have to design; that means, you do not know the specification a priori. So, when you are given a spec, how to meet those specs will require lot of understanding of devices as well as circuits. Because then only you can actually meet those difficult specs.

And therefore, design requires some understanding of basics of both devices, as well as circuit devices to a smaller extent, but circuit to a greater extent. So, this course will try to give some idea of good design principles, and to simplify the design process itself. This is course content available in the site itself, where there are some you know A to D and D to A some parts where even because that was old course design in which there was mixed signal circuit was part of this course. But now a new course is running mixed

signal itself. So, we are removed that part. So, we are little more time to do earlier things better.

So, basically, we will talk about mos models, why analog models are different from digital models, or how bad or how good they are we look into spice model. So, all of you should be aware of spice, I will not teach my. So, we will talk about a gain stages both with NMOS and CMOS. We will talk about cascade and the word cascode as the word goes there will show you, we will talk about basically references voltage and current, we will talk about a differential amplifier which is our bread and butter. And we will talk based on that opamp design, we look into frequencies in size vco based or PLLs look into little bit this here on interconnects, because this is becoming a very tough situation in 2010 or 11 ahead.

We will look into some testing layout issues, and also show you in the current context this word low power or actually the low voltage low power is written specifically, because the misconception among designers is that low power circuits are interest more interesting it is not actually. It is the low energy the worry is on energy not so much on power into time is energy. So, energy is what is worrying us the battery stores certain amount of energy it does not store power. So, how fast that will consume. So, we look into it, at the end what is this low power business.

The books which I use are not the only books which you should see, hopefully yes. But I like this razavis book by basic analog integrate circuits. Most of my basic part will be actually taken from razavis book which is a very standard all over the world. I have a edition one, but I think now there may be edition 6 4 5 whatever it is, buy the latest one.

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## Course content

- Introduction to Analog VLSI and mixed signal issues in CMOS technologies. Basic MOS models, SPICE Models and frequency dependent parameters. Basic NMOS/CMOS gain stage, cascade and cascode circuits. Frequency response, stability and noise issues in amplifiers. CMOS analog blocks: Current Sources and Voltage references. Differential amplifier and OPAMPs' design. Frequency Synthesizers and Phased lock-loop. Analog Interconnects. Analog Testing and Layout issues. Low Voltage and Low Power Circuits.

**Course Text & Materials:**

1. Design of Analog CMOS Integrated Circuits by B. Razavi, McGraw Hill
2. CMOS Circuit design, Layout & Simulation by Baker, Li & Boyce, IEEE Press, 1998
3. Analysis and Design of Analog Integrated Circuits, Gray, Hurst, Lewis and Meyer, John Wiley & Sons, 2003
4. Analog VLSI Signal and Information Processing, Ismail and Faiz, Mc Graw Hill
5. Specified journal & conference papers

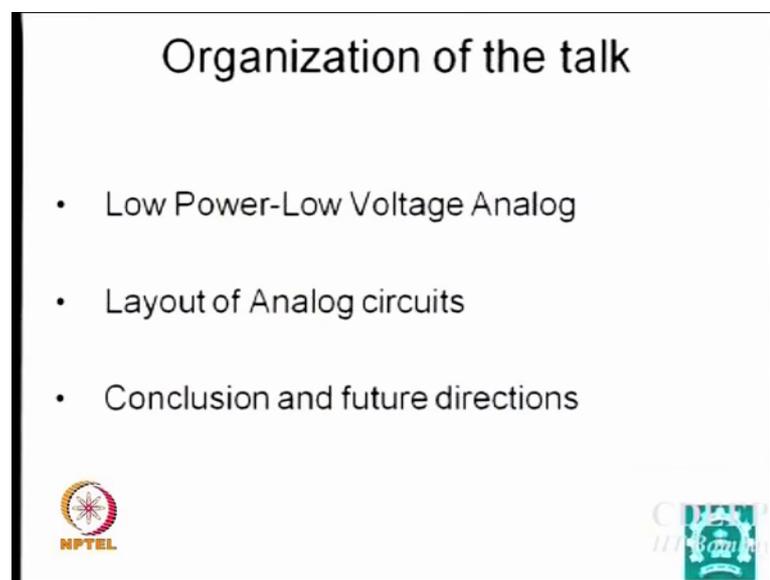
Then there is this book gives as I say mostly on the analysis part very strongly. Then we will talk about a something which is more practical, which is a book written by baker li Boyce. He is one of the pioneer researchers in the area of analog.

We will also look into a very old book old. In the sense it was available in my time. So, old that of course, the edition has change the authors, professor gray is still Paul gray is still there, but the other Meyer Hurst Lewis this keeps on changing Meyer. Of course, is older one, but the I think this new ones which Hurst and Lewis has joined. This is one of the oldest book on analog integrated circuits. And Paul gray was the chairman of AE department Berkeley, UC Berkeley also then the president of Berkeley. He is still there of course, he is old 81 years. So, his book is one of the best analytical book as far as the feedback theory books. So, those who are interested to know more about feedback, please carefully look into this.

The only problem is they are more from the old era. So, they are much more bipolar circuits, though they added now mos in last 10 year 5 80 years, but still their emphasis looks to be more on bipolars. So, I think that is the only reason why it is not so very popular my course itself says CMOS. So, I cannot say bipolar. So, then there is a book by Ismael as it is not available in the market. The reason is that it is a old book in India hardly anyone knows about it, and I being the one know about it when I was in abroad.

So, I purchased one. And many of the interesting research in the area of analog particularly, low power or convert systems. I think came from Ismael and (Refer Time: 05:40) people he is still with oi university. So, you can go on his site and figure it out of course, some journals and some conference papers. There are other books are appearing in the market. Please if you have you know some book which is good maybe you bring to my notice I will also look at it. But course does not require, because what I cannot change amplifier without 2 books whatever this amplifier will remain the way it is. So, do not worry if you have one of them is.

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So, basic analog design with CMOS and analog system we will also see something about low power low voltage. What is layout issue? Conclusion, this is only some overview.

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The slide is titled "Introduction" in red. Below the title, it says "VLSI of present era". There are four main bullet points: "Technology challenges:" with sub-points "CMOS/BICMOS/BIPOLAR" and "Silicon, Si-Ge, SiN and compound semiconductors and their combinations"; "Market needs" with sub-points "Wireless Systems", "Optical Systems", "Sensors", "High speed microprocessors", and "High speed memories"; "Analog designs are like custom designs" with a small circular icon; and "Power-speed is the challenge" with a small square icon. There are also two small logos in the bottom right corner.

**Introduction**

VLSI of present era

- Technology challenges:
  - CMOS/BICMOS/BIPOLAR
  - Silicon, Si-Ge, SiN and compound semiconductors and their combinations
- Market needs
  - Wireless Systems
  - Optical Systems
  - Sensors
  - High speed microprocessors
  - High speed memories
- Analog designs are like custom designs
- Power-speed is the challenge

So, wireless is the major driver for us all VLSI designers are actually indebted to people like you who use mobiles. Maybe 2 mobiles, these days' iPad, iPod whatever you talk. And all the WiMAX, Wi-Fi, whatever other hardware you create this is the way money is available. And that is why most of the chips, or most of the companies except intel for no good reason they fixed themselves to microprocessors. And I think another 30 or 50 year they may not leave that.

But all other companies have some way or the other has shifted to wireless products. Qualcomm is number one Broadcom is number 2, and lines of them. Even TI which was more signal processing have finally, entered wireless world last 10 years. So, everyone is looking into wireless. So, that is the major requirement. Then there are system which are specific optical system. People are now looking into changes from electrical signal to optical, it is not news. Quite some time, but more results are now coming. So, there are many systems which are optical systems, which may require our effort at least to interface them. There is a effort going on semiconductor, 100 percent optical signal system.

So, there is no conversions, no losses. But the material they are using is semiconductor, mostly 3 5 materials I am partly silicon, but everything on semiconductor. So, a link has been created which is 100 percent semiconductor based optical system. And no transition transactions the other area right now is sensors, and if you connected to wireless, and that

new word wireless sensor networks as if it is great. Sensors were known networks were known wireless were known. You combine you are in the world top 10, that is what this. So, we are right now people are working, but sensors can be of any kind any energy to any energy they are sensing you have to sense.

There is also a cad with the what is the word transducer and what is the word sensor, there is lot of fight goes on, basically sensor should only sense. That is the word is, but most people believe sensors means a transducer with a conditioning circuitry, or what you call amplifier signal everything on chip or everything together is a sensor. This is the way they think I am not saying correct all right. So, there are many systems, which are requiring sensors now based connection to circuits. So, these are markets. And of course, sensors high speed microprocessor, 4 gigahertz. If you give you say you need 6. You need 6 you say 10 why because that videogame I want to kill that person faster somehow.

So, that microprocessor speed somehow is the marker for everyone how fast. So, huge effort is on high speeds. And of course, to come match them then you need data transfers as fast as processor is asking, you need look for high speed memories. So, what is the difference between digital design and analog design? In digital design if you are I think we are done some digital circuit, but the other course is running 671 VLSI design. So, whether we keep saying that look digital design is basically hierarchical; that means, I can have system break into smaller, and one side design grind the smallest part I design back bottom up.

So, and gate can convert to xor, xor can convert to large, and we can go up to any system. So, the idea in the digital system once design you can read you do not have to redesign. Because and gate does not change very much, except for it is driving that is current how much it needs or diode out. So, these are more you know what you says semi-custom available you can reuse it, but analog there is no such things every system. You ask you have to design it. So, it is called custom design. So, something every customer requirement has to be met therefore, analog designs in general are custom design. And in general, mean people are now trying to makes equivalent effort like, can we make VSDL instead of their ASDL analog high-speed hardware description language can we do similar silicon compilers for analog.

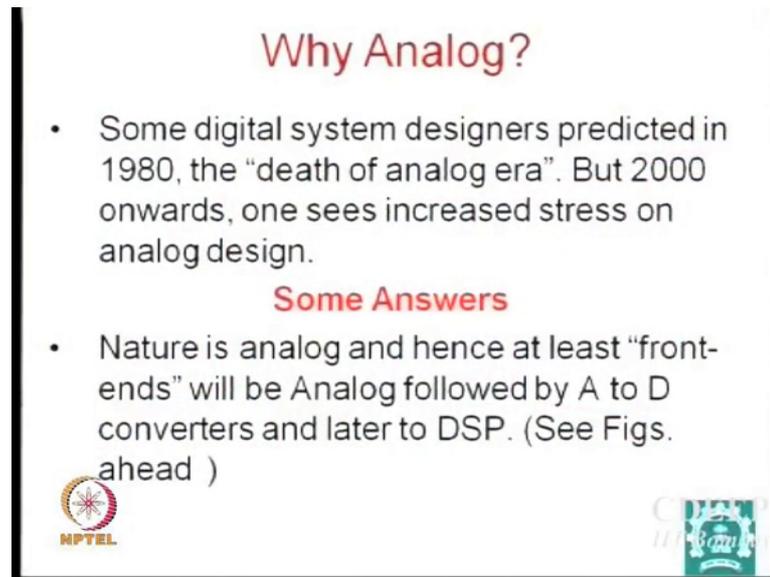
So, there is an effort going on to do replication of digital into analog. But as of now most of the circuits are actually designed transistor wise component wise. That is the strength as well as the weakness strength in the sense for a teacher that is the best thing because now he sees transistor in digital you do not see a transistor. Comparator and xor either through transistor decay. So, something you can see what is happening is analog. And therefore, you can design, oh if I change size if I changed mobility I change  $v_t$ , what will happen is my  $g_m$  is higher. So, I am looking one to one what specs I am looking for that digital does not require because digital of course, is the easiest designs.

So, the point is that it is a custom design and therefore, very interesting because every design requires some way you are so called man satisfied in his ego if you say yeah, I understood. It whether he understood on another issue, but he feels very comfortable that yeah, I on understood. That is why all these quasars pulsars, these recent surround experiment what is great going on if that David atone is not existing you mean world would not have been a world is still there.

Now, we are worried is that kind of his boson is available, that makes fun for us. Because then it is oh so, it is statistics is something like this. It follows, but it is like that, but it has a mass. So, it is not like a fermion. So, this satisfaction that we understood is always with us. And I wish IITn's do not leave this part in their careers or in IIT. Main do not become robots, remain humans. If you do not know few things is, but what you know you should know better. What you do is irrelevant.

But how do you do matters. So, what subjects you do in life what you do is very irrelevant. Otherwise all kinds of people would not have been there successful, but how do you do matters. So, work for the best of yours in whatever you do, that is what is important as human. And in further more to learn. In analog circuit power and speed like in digital is also important. The word in the speed in analog is converted to word bandwidth which is essentially digital we call speeds.

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**Why Analog?**

- Some digital system designers predicted in 1980, the “death of analog era”. But 2000 onwards, one sees increased stress on analog design.

**Some Answers**

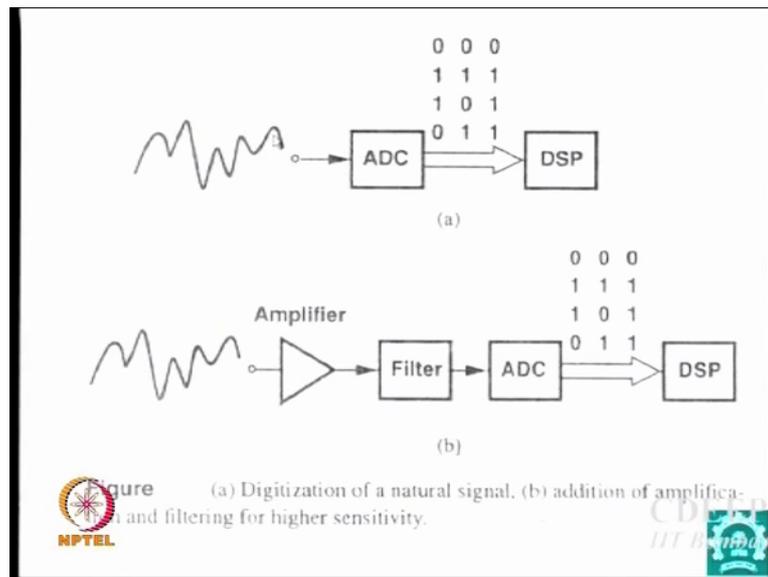
- Nature is analog and hence at least “front-ends” will be Analog followed by A to D converters and later to DSP. (See Figs. ahead )

So, few queries; questions are always asked why analog? So, in 1980 many of the digital system designers, they started saying analog is dead. That is, it end of it. But 2000, you see more and more papers more and more industries are entering analog. So, something has changed or something associated, that analog design be relooked into. The reason probably is we are now trying to see harness more of natural resources of natural systems we are trying to play with them. And nature essentially high is everything in analog. That is why the question came whether big bang theory is or solid steady state theory is because nature does not like bumps. It always goes one after the Darwin’s theory. That is how we became humans from all the other races.

So, nature is analog. So, even if you process every signal digitally at the end which is better in many cases. The front end will be always analog, because signals will be analog. So, analog is a necessity, because any DSP ahead will require digital data, which it can receive converted from analog signals. So, that is one reason, here is an example.

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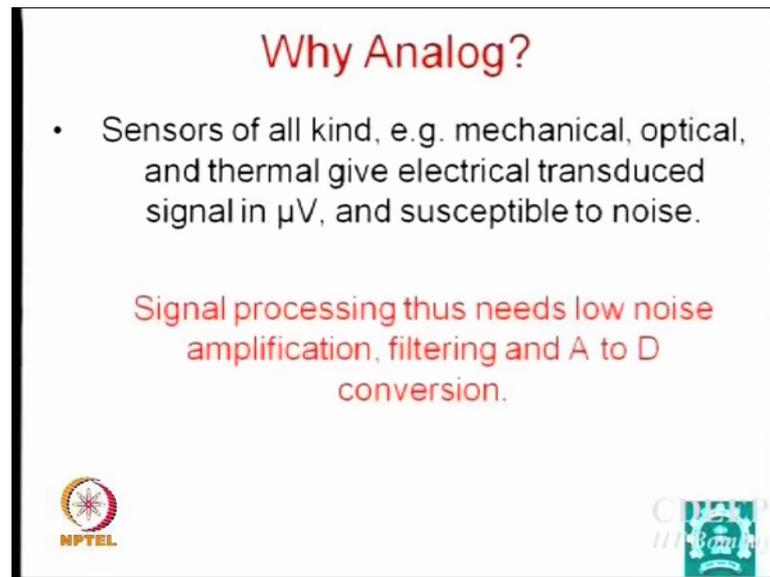
I have an ADC, and I have some input analog. If I convert it through ADC, maybe I will get the same truth table for it or data or something like this which may be fed to DSP.

The problem is that the signal here the strength of a signal or a amplitude, when you convert through ADC, and if you have done ADC sometime, you know the there is something called inl dnl. So, it how much error it will create, because if it does not cross the threshold, it will not go to the next state; it may remain in 0 it may not show you one where it works. So, it should cross. So, it is very unlikely that every time, you will get correct conversions, because the analog natural signal may not be known to you and has it actually known amplitudes.

So, the best way is therefore, amplify analog signal amplify. Once you have amplified the signal. Now you are almost sure what are the levels, and if you now convert it and maybe other components some frequency components you can cut off from there other than the desired signal, you put a filter pass through ADC you get a digital data. You are guaranteeing efficient way of converting an analog to digital. So, that is why you need an amplifier, you need a filter before any DSP or ADC can be applied.

So, that is why analog cannot be just brushed aside there are natural signals required digitization will requires at least amplifier, filter and an ADC.

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**Why Analog?**

- Sensors of all kind, e.g. mechanical, optical, and thermal give electrical transduced signal in  $\mu\text{V}$ , and susceptible to noise.

Signal processing thus needs low noise amplification, filtering and A to D conversion.

Now, go further going ahead, as there are sensors of all kinds mechanical mems which is very popular these days in our group. Optical thermal and they all energies are transduced into electrical signals, because we are electrical people. We can anyone can convert mechanical to optical and get away, but we will not probably there because we will like to see something signal microvolt nanovolt or some volts or some currents.

However most of the outputs of sensors when converted or otherwise without amplifiers will be very, very weak. And therefore, has huge percentage of noise on that. So, obviously, the noise part has to be removed. So, the all the analog system which we create must be low noise. Because otherwise they will pick up noise and add noise to it. And therefore, the analog signal people must worry much more on the noise, then what digital people work at now. It is also not correct, but this is what I said, this is my statement.

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### Why Analog?

- Digital data transmission on a long distance leads to “distraction”. Hence analog kind of trans-receiver will be needed.
- Data from HDD is extremely “weak” in separating “1” and “0”. Amplification is thus necessary.
- Wireless receivers receive very “weak” signals from antenna. Hence amplification is needed.



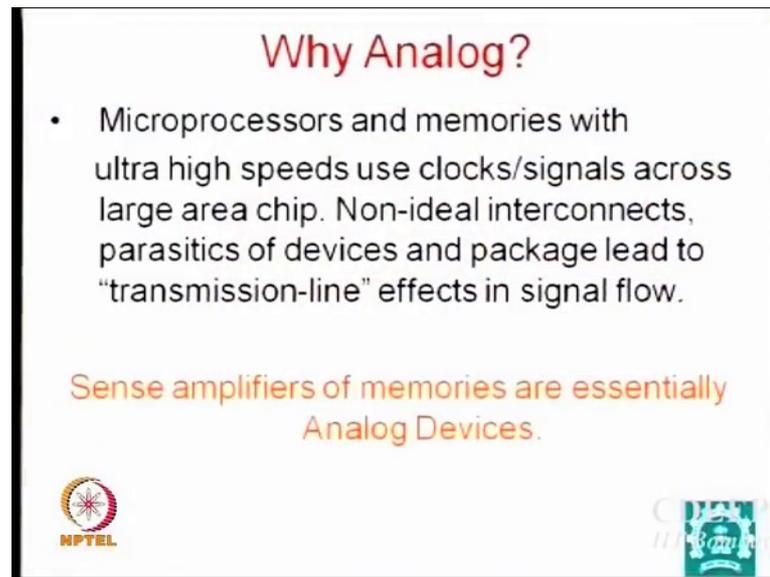
Digital data normally gets if you transmit very long unless you have a repeaters, it gets the torture or called distractions.

So, it is better if you have a transceivers of analog kind, because they will be faithful to your signals always. How much additional hardware you will require? And how much money you may have to pay? Maybe another issue, but analog transmissions will be take a cable home television. You will have a very good signal coming you see a beautiful videos. You actually connect a normal computer and put a TV in disc, you will see it gives a good figure, but it has a huge lines in between. Digital because the pixel to pixel it picks up.

Now, this is essentially one says that analog signal processing is far better than digital signal. If you see a hardware harder hard drive disk, you know many times over the time because the magnetic in many cases. The signal becomes very weak data is very weak. So, it becomes very difficult to know ones and 0s there. And therefore, what you read may not what you wrote. So, you need some amplification a priori before you read it out.

Wireless for example, the antenna which your mobile has a very small antenna which has very little directivity; that means, it has a very small antenna gains. So, the signal you receive is very weak. So, the first thing you have to do is amplify because otherwise that signal is less than few microvolts. So, your circuit cannot actually behave also. So, need an amplifier right there after antenna. So, I am trying to convince you that why analog.

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**Why Analog?**

- Microprocessors and memories with ultra high speeds use clocks/signals across large area chip. Non-ideal interconnects, parasitics of devices and package lead to “transmission-line” effects in signal flow.

Sense amplifiers of memories are essentially Analog Devices.

Microprocessor memories with ultra-high speeds use clocks and signals gigahertz. You are say 4 gigahertz as a system claps for intel new processors maybe 60 gigahertz.

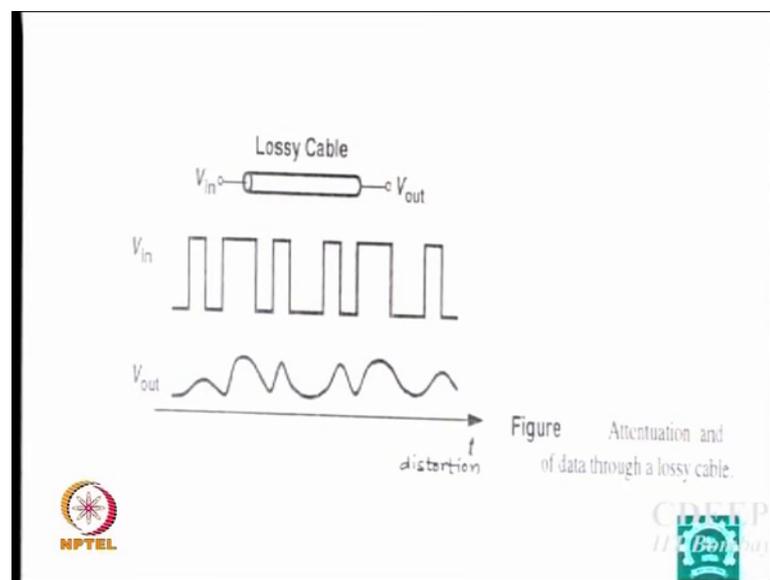
Now, these kind of signals are such a high frequencies. Do not remain pulses. They actually get mashed up, and they look more like a analog what is the difference word analog means continuously time varying signals are called analog. Step signals are called digital 0 1 or maybe multi value. Whereas, in analog amplitude keeps varying or frequency keep varying with time that is why continuous. So, your clock if you see now it is more like a continuous kind of this. There is no fixed wave. It is something like this wave its. So, as much you may like you are still doing analog signal processing even in the high frequency domain. The interconnects which is the major worry right now in any single chip right now, they are used a rc or rlc parasitics now transmission line effects are very, very strong.

And if you are done your theory of in waves which I wish you have. We will realize that transmission line theory it creates you know the impedance match reflections VSWR words which we use in clear they do now come into picture in our own circuits now. And these are basically analog signal processing. So, what we are saying even in a very high frequency digital domain, you are doing analog signal processing anyway. Now if you have a memory, I hope you have done some course in particularly sram or dram, you say there is a or any memory (Refer Time: 21:52) there is a sense amplifier. The idea of sense

amplifier is you do not have to see full voltage swing before output is given to you. So, a senses one or 0 faster.

So, when you sense it, it has a some kind of a defame going there; which is an analog device. So, you look at systematically any digital hardware even now. You will find one way or the other you are directly or indirectly using analog processing. So, learning analog is not very bad worthwhile. At least QUALCOMM Broadcom lookup to the (Refer Time: 22:30).

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For example, you have a cable, and you are inputting a signal  $V_{in}$ , and expecting an output  $V_{out}$ . It is a good  $V_{in}$  signal good pulse is going, but what you see at the output if the cable is lossy which it will be most cases.

There is nothing called lossless cable. Low loss cables is possible, but there is nothing called lossless cable. So, if you even if you are lossy, the output you are going to get is not digital you can see what signal you are actually transmitting. So, essentially anything now you do at high frequency in particular, you are actually worried more of analog problems than digital convince means theory (Refer Time: 23:20) you must know in mind. That is this course really relevant other than the job which of course, it is I may telling.

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**Why Analog?**

**Question:**  
Is analog design more difficult than digital design?

**Answer: Yes!!!**

- Digital Design
  - Large noise margin
  - Trade-off between power and speed (and area) only
- Analog needs multi-dimensional trade-offs between
  - Power, speed (frequency), gain, precision (drifts), power supply voltage

The slide includes the NPTEL logo in the bottom left and a university logo in the bottom right.

So, the question finally, can come why analog question for me is analog design more difficult than digital design. If you are asking me, when I teach the analog course, answer is yes. The reason is obvious, in a digital design if you mostly it is inverter based or nand nor gate based. If you see the voltage levels which are allowed in digital. So, let us say  $V_{dd}$  and 0 are the uppermost and lower most signal levels up to  $V_{t0}$  can go. And even up to half of  $V_{dd}$  upper voltage can go. Still it will be recognized in 1 and 0s that correct.

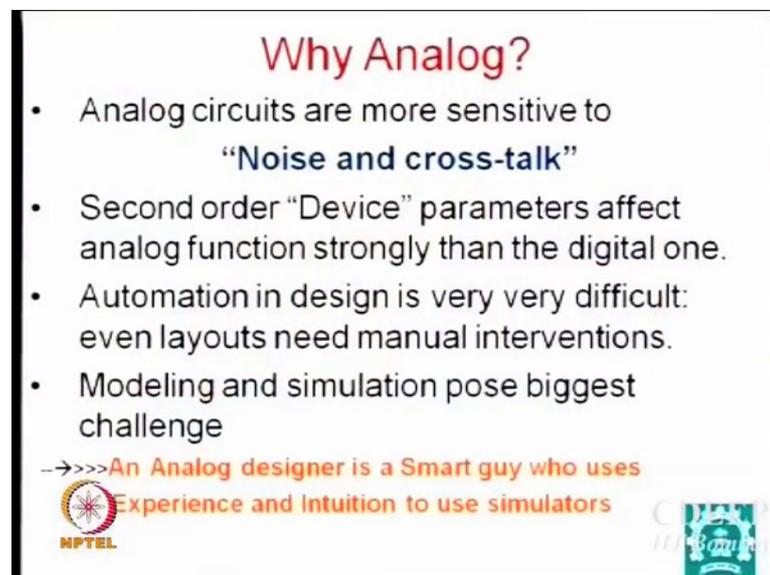
So, there is a huge noise margin available. So, signal is not reaching peaks or going not going to 0, does not matter one 0 does still recognizable. Of course, there are 4 corners high speed c in case of CMOS from a p slow high n slow p slow p fast I fast and other 4. As that margin is too big, if you fit inside that 4 corner you are safe everything will work essentially related to sizing as well as temperature. So, if you do that process and this together, if you fit within that enough margin is available to you, ideally which has  $V_{dd}$  by 2 margin anything less than one and anything greater is 0.

So, it is a fantastic system. So, you are not worried too much. Of course, there is a trade off still goes on there. Their major worry is power connected with speed larger the power, larger will be I mean it will be high speed. This is very obvious trivial in some case, because in most circuits the current which you are using is to charge the capacitor. Larger the current  $cdv$  by  $dt$  is larger time will be smaller as great as that. So, faster means push current, higher currents higher current means higher power.

So, it is very simple that power cannot be low as well as speed can be high, but that is what digital people want. And that is what we keep doing that how to beat the system. Low power high speed how do you do it that is the game. So, how to fool a circuit? To do that externally you feel that I have achieved it. Internally things cannot be changed, but externally you still feel oh I have achieved low power and relatively high speed the games. Of course, you can have a third parameter their area of the chip or area of this power circuit. You create which can barter with that, and can adjust to one of them whereas in analog it is not just bandwidth power.

It is power, frequency, gain, precision, which we call drifts supply voltage all of them actually affect the outputs. So now, when I am designing something, if I catch one the other may go here while. If I have catch 2 or 3, the other 3 may not be within my hand. And therefore, design of a analog system really requires thinking. That is why I said that word thinking more essentially means, there are some people like thinking. So, for them analog design is simpler. Because that is what they want, but in general people want to bypass thinking then digitals are the best analogs are not.

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**Why Analog?**

- Analog circuits are more sensitive to **“Noise and cross-talk”**
- Second order “Device” parameters affect analog function strongly than the digital one.
- Automation in design is very very difficult: even layouts need manual interventions.
- Modeling and simulation pose biggest challenge

→>>> **An Analog designer is a Smart guy who uses Experience and Intuition to use simulators**

There are more problems with analog is well, analog circuits are extremely sensitive to noise, and cross talks. Cross talk I suppose you a little bit of a pair if 2 lines are going together, the signal on one line can interact with signal on the other. That is called cross talk. Device cross talk occur if the signals are moving opposite direction. If they are in

same direction lesser cross talk, if they are in opposite direction, it is  $x$  minus  $y$ ;  $x$  plus  $y$  kind of situation. So, cross talk is major worry in most of the circuits now, digital include or other digital is worse right now.

Rather putting too much of interconnect there, too many lines going on. Particularly like DSP it has a more lesser circuit more interconnects. So now, at such circuits you will find the problems arise only on the cross talks. So, how to get rid of them? One method of course, they suggest that put a ground line every between 2 signal line area. So, paid price, which we do even now, A noise, any line picks up you know like you put a wire it picks up some voltage essentially is noise voltage thermal if nothing else analog that noise is there is no margin there.

So, any noise is also a signal. So, if that goes it also gets amplified or whatever modification you do. Noise also will get modified. Nothing can be done. In digital device second order effects, because now they are also important in lower technologies, but earlier we used to say that. They will not so much important because of huge noise margins available, in the case of digital. Analog any variation threshold go goes by less than point one volt. Current will be proportionally increased by that much square law.

Now, this means now suddenly you figure out, small change there we did not carry, here that has immediately  $g_m$  has change, bandwidth change, sometime it will not within what your wants or the out next stage may not work. So, there are issues which only analog has to have tackle. So, automation becomes therefore, difficult I am not say it is impossible but difficult, because every case has to be handled. Even in layouts which are generally done by layout editors final before mask is made. Most digital people just you know go through a layout editors and generate patterns very fast. Analog even if you do once, you will have to make 100 time intervention to, oh this will may not work, but try this now.

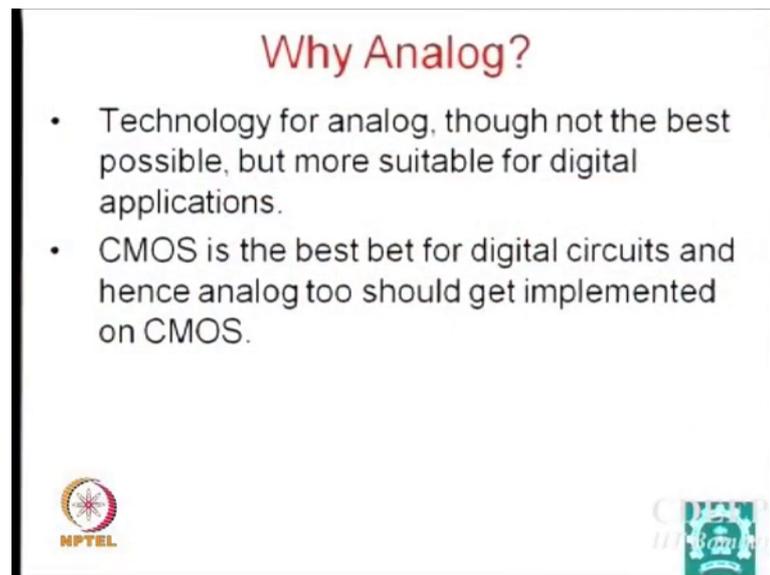
Resimulate again with the new one extracted. So, there is game in analog layouts also huge problems in analog layouts. We shall show you this part later. In the models which are good for digital are no good for analog. They show you some of them. For example, there is a saturation parameter called  $\lambda$  which you within the current device; in the opamp design case at the change in  $\lambda$  is  $\lambda$  to the power 4 in the this change.

So, what you thought 500 gain you may get 5 or you may get 500 or 800 depends on which lambda needs.

Lambda changed r 0's. And if you may products, it will go to the lambda the power 4. And digital nothing called fetch we actually leave lambda here that lambda cannot be left. So, analog designer therefore, in my opinion is a very smart guy who uses his experience, and to a great extent intuition this is what humans are we have intuition. That is what we differ from animals. If you have no intuitions we will be as bad. So, when you use even the simulators, you have to have great experience pat knowledge and intuitions to design the newer system.

So, that is the difference between analog and digital.

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**Why Analog?**

- Technology for analog, though not the best possible, but more suitable for digital applications.
- CMOS is the best bet for digital circuits and hence analog too should get implemented on CMOS.

Now, what is major worry for analog designers is this. Analog independent analog states are very few demand opamps are made and made, and they are sold. Only instrumentation people buy them. Very few such other systems buy opamps per say independent. So, I cannot have best of opamp design like ad 5 7 6 very low noise opamp I can design I can make I can sell that also at the on a board on a single chip on that. But a total mixed signal system, 80 percent of the part on that chip is digital or maybe more at times.

So, what who will decide the technology? The digital people, the digital technology which we call smaller channel link technologies nanometers 11 you want to go 0 nanometer mos transistors now. So, you want to reduce, but surprisingly when we do analog design we figure out that larger the link better for us. Now here is the first conflict comes. I want to work on 0.35 microns, they say work on 16 nanometers. Now here is an issue.

So, the technology will be 16 nanometers, and now I am told design your analog as good as what I am asking on this technology which is not good for you. So, that is the biggest challenge analog people face. If you are left alone maybe I will use bipolars which are the best analog components, but I will not be to ask to do that I say area how do we do that is the way pleasurable. CMOS of course, is the best bake for digital circuit. And then whatever we do analog has to be used now has to be designed only on signals it is not that I cannot. Design on any other technology or better or worse by CMOS maybe even better.

But because 99 percent digital mixed signal circuits are digital based, I will have to work on all the time on CMOS because they were consumers. So, there are issues which certainly are cropping up not, because analog is weak or something. You are given a bad tool and asked to design a very good system. That is where and, but that is the interesting part because it is not easy, it is not easily thinkable. So, you your best comes out I can beat the system, at least I reach what is masking.

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**What is Analog VLSI Design?**

- Analog IC design is the successful implementation of Analog circuits and systems using Integrated circuit technology.
- Unique Features of Analog IC Design:
  - Geometry is an important part of the design
  - Electrical Design Physical Design Test Design
  - Usually implemented in a mixed analog-digital circuit
- What is Analog VLSI Design?
  - Analog is 20% and digital 80% of the chip area
  - Analog requires 80% of the design time
  - Analog is designed at the circuit level
- Passes for success: 2-3 for analog, 1 for digital

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So, finally, in the end analog IC design is successful implementation of analog circuits, and systems using IC's. Their unique features are geometries an important part of the design, this is most important which is nothing in digital, but in analog the geometry the layout is the most crucial part of the design. Even sizing is very, very crucial.

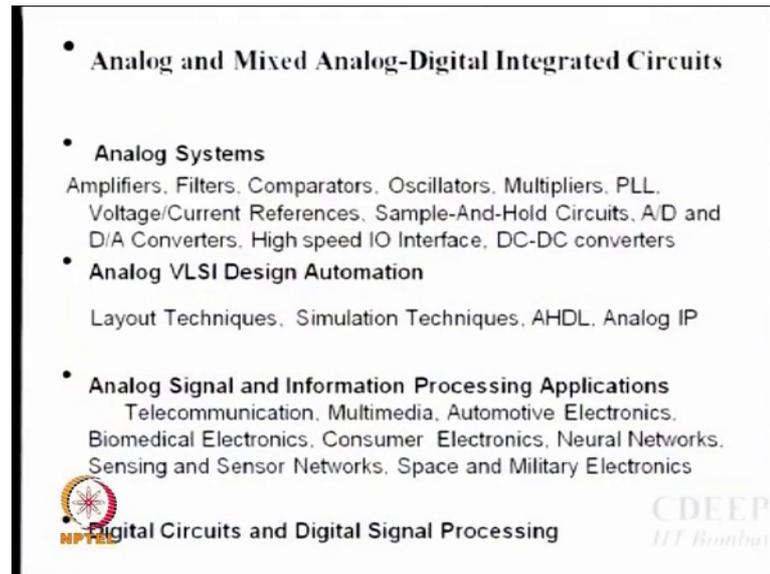
You create electrical design from there you go to physical design and from there finally, when the chip is made you tested you have to create test vectors, which you have to test this. So, if all the 3 part as in digital you will also have to do it in the case of analog. As I said they are to be implemented mostly for mixed signals, and as I said 20 percent analog 80 percent digital and a chip. So, 80 percent majority (Refer Time: 34:54) heads majority governs. The democracy head, because of that analog circuit have to be or analog design has to be on a transistor or a circuit level more importance has to be given. Whether pass means after I design, and I have fab and I have test.

Then I see what specs I wanted and what did, I get it is called one paths. Most digital circuit with because of the experience and expertise available now across the world, in one pass most, circuit will come out. At best 2 inverse designers if you are not a good designer; that means, we are not good digital designer, that what you should avoid in my class, but that is what they industry if it is good, who can copy best is the best digital designer. You see design nothing better because it has worked grow up for you also.

Whereas, in the case of analog it may require 2 passes it may require even 3 passes. So, cost is very high for that.

So, that is why I keep saying analog. So, what are the systems in mixed signal or analog we have in.

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- **Analog and Mixed Analog-Digital Integrated Circuits**
- **Analog Systems**  
Amplifiers, Filters, Comparators, Oscillators, Multipliers, PLL, Voltage/Current References, Sample-And-Hold Circuits, A/D and D/A Converters, High speed IO Interface, DC-DC converters
- **Analog VLSI Design Automation**  
Layout Techniques, Simulation Techniques, AHDL, Analog IP
- **Analog Signal and Information Processing Applications**  
Telecommunication, Multimedia, Automotive Electronics, Biomedical Electronics, Consumer Electronics, Neural Networks, Sensing and Sensor Networks, Space and Military Electronics

 Digital Circuits and Digital Signal Processing 

Analog system which we have are amplifiers, filters, comparators, oscillators or frequency synthesizers, the new name, multipliers, PLL's, phase locked loops, voltage current references, ample and hold circuits, A to D and D to A converters, high speed I/O interface. This is another area where much of the work going on is high speed I/O, and DC to DC converter. Now this word is very interesting it is has been asked by me across IIT faculty introduced for a assistant officers.

Do you regards to them? Who didnt answer if I have 5 volts would supply and I want to volt a one volt. Put a part we have done in second a lab at register divide the old minute. So, DC to DC, DC say AC, AC you are not wrong this is the one important parameter. So, the DC to DC converter, and it has become very important even for digital norm because on a digital hardware, now there is a what we call power supply unit or power management unit. Which essentially create variety of voltages for variety of blocks of the digital part.

So, there that is a analog part. That is why I keep saying. Analog is secondary 0. We want to have analog design automation some of you can think over it. We can have automated layouts. We can have better simulation techniques, then synopsis or cadence giving you for analog. You want to create hardware description language similar to digital, if possible. And the best of course, is you design and keep record of that it is called intellectual property. Probably you can reuse it. You can sell IP's itself. Do not make chips, designer IP test I have test and say this is doable.

So, I opamp from atmel you can actually buy an IP for an opamp, you do not have to design, you find out on the space which atmel number matches require. You just ask pay a hell of money for getting that, but the effort of design is 0. They pay for it. Someone else does not need to use it. So, there is another way of doing analog designs. Most Indian and abroad companies actually work on IP's. Either they create IP's or use IP's. So, those who create IP's, IIT should join them because there is where the effort is interesting affordings. If you look at the signal and information processing application for analog almost every telecommunication, multimedia, automotive electronics, biomedical electronics, consumer electronics, neural networks, sensors sensor networks, space and military applications or electronics. And of course, in all digital and digital signal processing itself now you will require analog study.

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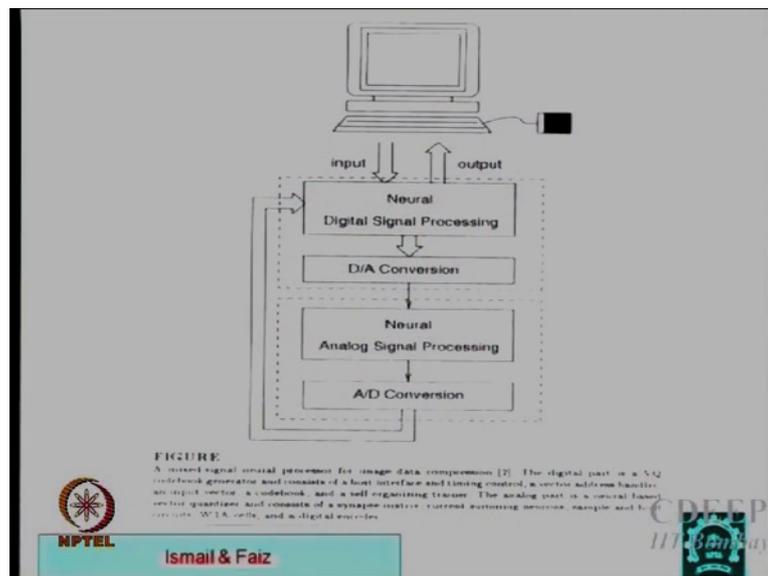
### Mixed-Signal VLSI Chip

- Mixed digital/analog : “core” is analog and I/O is digital, e.g. neural signal processors. (See Fig. )
- Comparison of analog and digital VLSI (See Fig. )



There are 2 kinds of mixed signal which probably many of you are not aware. Most of the teachers here are including me, mixed signal means mostly digital part analog. But there are other kinds of circuits available which are useful also. Particularly for newer applications of bio, which are neural base. There most of the core is analog, and some inputs or outputs are digital. So, these are also mixed signals. Here analog is a major component. So, neural processors is one example, we show you the figure. And we will also show you some comparison of analog to digital.

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This is a typical neural processor, you can see from here. This is your computer or say data, from where you can create digital data you can have a DSP some kind of neural DSP processing. Convert to analog then most of the processing is the neural analog. Then again convert to A to D for feedback to digital. So, that the system is stable as well as to stick. So, if you see it, a digital part as a vector quantizer. Some codebook generators which comes from PC's and through neural processors then there are a host of interfacing required timing control digital requires. So, is analog requires. If you see the analog part particularly, it is a neural processor requires some kind of vector quantizer again. And it concept of synapses and matrix if you are done a course on neural networks, you know about it maybe I will show you is well.

You may require summing of currents for neurons. You may require sample words, and you requires encoders, and WTA cells communication. People know much about the

word WTA what is it? There is a famous song from 25 years ago, abbas song. First song winner takes it all. So, WTA of course, in bio it has another word, but in case of this winner takes it all WTA. So, it is a majority circuit which takes winner.

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TABLE  
Comparison of analog VLSI with digital VLSI in terms of cost, power, and computation density. (©1998 BYTE)

Analog VLSI is strikingly superior to digital technology in terms of cost, power, and computation density. (Estimated by Frederic Faggin)

	ANALOG VLSI		VS. DIGITAL VLSI			
	Cost (MCS*/ $\bar{D}$ )		Power (MCS/watt)		Computation density (MCS/ $\bar{D}$ )	
	1991	2000	1991	2000	1991	2000
Conventional digital	0.002	0.1	0.1	10	0.2	10
Special purpose digital	0.1	4	10	10,000	10	1,000
Dedicated digital	5	200	500	50,000	40	3,000
Dedicated analog	500	20,000	50,000	5,000,000	4,000	4,000,000
Human brain		$10^{10}$		$10^{10}$		$10^{11}$

\* MCS=1 million connection updates per second  
 \*\* This calculation assumes that the cost of a human brain is \$10,000,000

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So, these are the part of a neural processor, which requires more analog processing, than digital processing. This is the old slide of 98. So, it is not very valid. The point we were trying to make then why it is 98? Can you guess this word 98? In 1998, this course was written by me and first time taught in IIT, or rather any IIT. Everyone copied and kept saying we have started, fair enough. All teachers do the same. We also took someone from Stanford or MIT, and then we say we have done it. Other IIT's doing for me saying is equally good. At least they have seen my course is good enough.

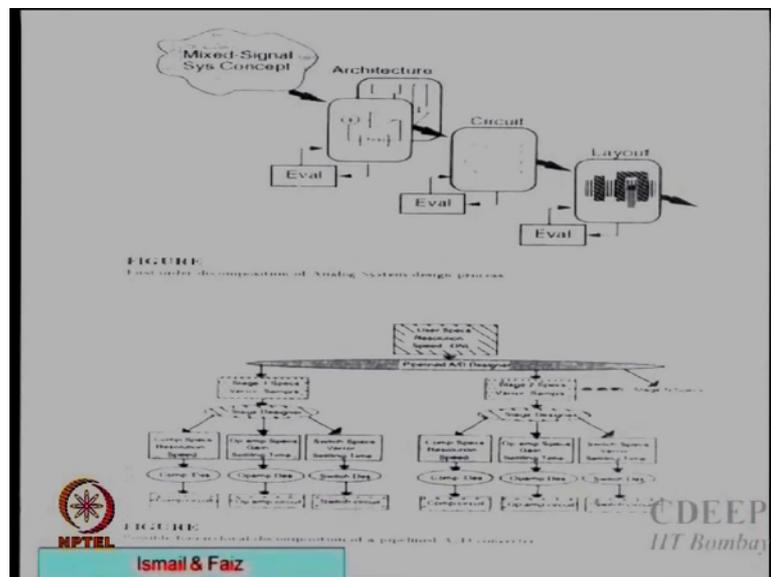
So, this was the time. And so, this was a old slide. So, I just wanted to show you. So, from this you do not have to go. The idea is to show here is that everyone believes that the analog processing is costlier. It is not true. If you look at the million connections updates per second on instruction calculation per second, analog is better than digital. So, to some extent this idea should get out that digital systems are far superior to analog system. This is only my word for you because people have started believing that that is why digital is the popular.

Now, it is very simple cheaper that is true. But otherwise if you are larger processing even this can match you as much. But with larger analog there are more problems. So, it

is not catching up, but by the pass for a theory goes analog signal processing will be far better any day. You see the numbers human brains require 210 to the power 9 million connection updates per second. We are still analog at least we are reaching 20000 digital 4 5. So, we are know where reaching to the nature. As well at least we are coming closer to the nature.

To some extent analog is still very much relevant for some are getting, this is taken from a smile phase.

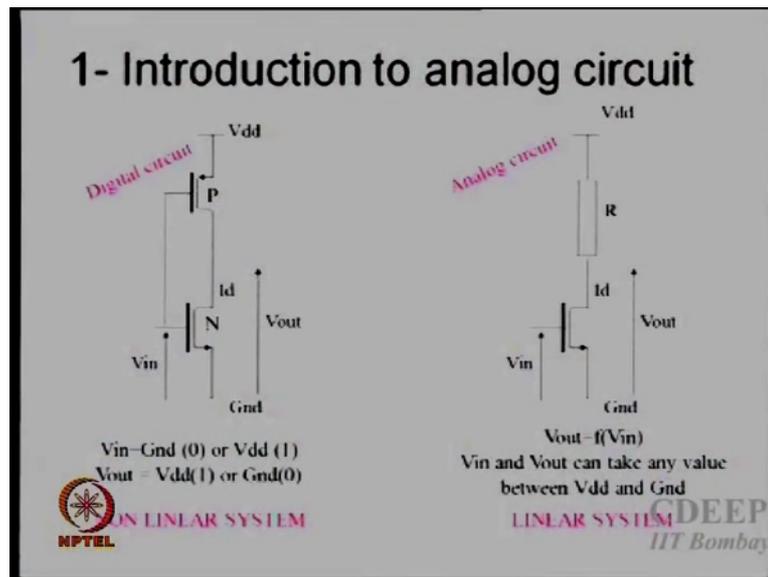
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This is just to give you I want to make a similar logic design kind of thing for opamp this is my aim. No one has done it. No one has succeeded. You have a mixed signal concept. This is called top down design bottom of implementation as we do in digital Rhonda c can be doing analog. So, this is the flow from concept you can create a architecture each architecture can be created to circuit blocks. You should have some evaluation blocks feedback to each and from there to circuit maybe reevaluate and feedback to mix.

The flow which we follow in digital can be follow similar way in analog is ultimate for us. We are not right now we do have hazard way we design and say it is.

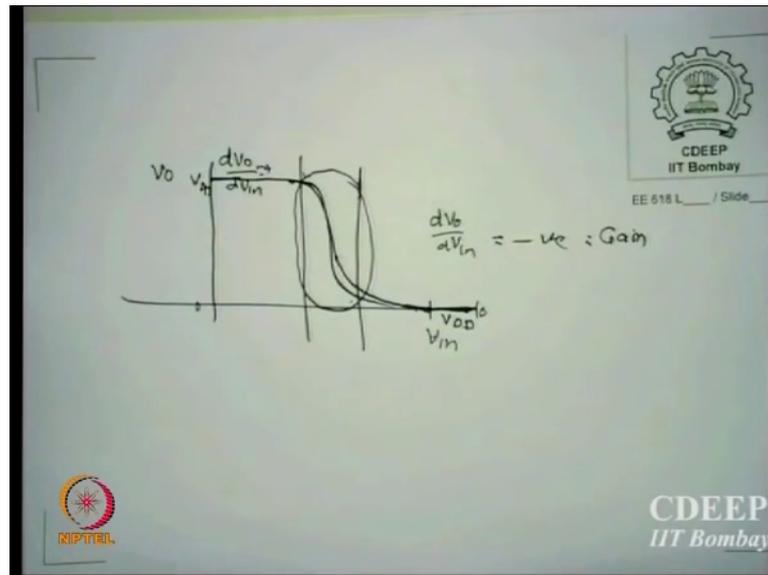
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So, if you look at the analog, here is the typical digital inverter on your left. P channel device and channel CMOS inverter, depending on the input low or high. P channel will be on or off correspondingly output be 1 or 0. So, very 3 will inverter circuit which is digital; the  $V_{out}$  may not be as  $V_{dd}$ , where  $V_{out}$  high may not be  $V_{dd}$   $V_{out}$  low may not be 0. But possibly we want to make it and CMOS. It comes very close to one and 0 as they are.

Whereas if you look at analog the basic circuit is an amplifier, actually this is also an amplifier, there is no difference. I will show you the what is the difference this is an amplifier, which has a resistor which can be a transistor if you have and you have a n channel driver please remember the word driver is used by us, which actually puts the out input receives the input and puts to the output. So, it drives. In this case one cannot say n channel is the driver. Because the other signal is also connected to p, whereas, in this case this transistor is a driver. In NMOS inverter yes, there will be a driver to understand a load as it is. This is like an NMOS inverter is.

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So, the what is the fun part in this is this; if I plot for an inverter or an amplifier  $V$  out versus  $V$  in we have done this in many courses.

This is normally  $V_{DD}$ , this is normally  $V_{DD}$ . There are of course, there is a 5 regions, but 3 shown here. Anything  $V_{in}$  less than somewhere here  $V_{out}$  remains high anything beyond very sorry, we did is here not here somewhere. Anything beyond certain value of  $V_{in}$  in the  $V_{in}$  becomes  $V_{DD}$  this becomes 0. This is what normal inverter shows. And we normally do not worry about this part. The reason is we are only worried about these levels in digital 1 and 0. So, input goes one output should go 0 output input goes 0 output should go high. It transits we do not care too much we do, but not so much.

If you see the gain here  $dV_o$  by  $dV_{in}$  is how much? 0 same way here. So, this is 0 in these 2 regions. But what is here,  $dV_o$  by  $dV_{in}$  which is gain with a negative value is my gain. So, if you are looking for an amplifier; obviously, you cannot operate on this region and this region. You can only operate in very small d. And if you use a CMOS you can see this will be even sharper like this. This is very interesting; that means,  $dV_o$  by  $dV_{in}$  is very high in transitions. So, analog circuit only work in this small input range, that is why small signals, where digital can go from 0 to  $V_{DD}$ .

So, gain part only comes in a very small inputs. So, we are worried all the time about this region in the case of analog. Is that clear to you? So, the transistor must be remain biased in this region to keep amplification in digital you do not bias because you are not

interested in gains anyway. Of course, it does have influence on speed, margins I am not trying to say digital does not get affected by that. In fact, depends on size it may shift and it may reduce the margins as well. But typically, digital be damn care, because we are only interested in the 2 ends. Analog, we are only interested in between which is the gain function.

So, one has to accept that, the first difference between the 2 circuit is the input range. Otherwise this can be used on an inverter this hole as can be used an inverter. So, as you can say this is an inverter because it allows you to shift we did it to ground whereas, this will input is limited, and the bias which is not shown here is exactly in that range in which gain is possible. Is that clear? Exactly that is the reason why analog is interesting.

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Digital circuit	Analog circuit
Highly non linear	Highly linear
High noise immunity*	Sensitive to noise (... pickup, crosstalk ...)
Immune to power supply variations*	Sensitive to power supplies
Carries only one bit of information	Carries n bits of information **

**NPTEL** up to certain limits !

\*\* = function of max. signal range versus noise level

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If you see comparisons the digital circuits are highly non-linear you are just seen the characteristic very non-linear.

Linear means  $dV_0$  by  $dV$  in except at the edges it is constant. So, linear another second-year student who have passed,  $Y$  is equal to  $mx$  plus 3 see is linear. But it is not a linear system. So, do not confuse between linear linearity and systems. So, it is a highly non-linear, high noise immunity, immune to power supply variation, because as I say margin high and immunity you for a trans percent, who cares? And one bit at a time is the information transfers. So, no worries.

If you look at the analog, it is very linear that is the gain is required; extremely sensitive to noise. Now you can see anything now on this will also get amplified. So, any small signal also has a larger gain seen by it. So now, apart from signal, any noise also will come to you. Whereas, in the case of digital data. So, it is very sensitive to noise and therefore, worry; any power supply variation is also worrying because it will directly reduce the currents and therefore, gm's and everything and carries more than one bit of information and therefore, it is multi bit transmission.

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**General Design Issues**

DIGITAL	ANALOGUE
<ul style="list-style-type: none"> <li>• Irradiation results in additional speed degradation (<math>V_t</math> drift, mobility degradation)</li> <li>• Power consumption change before after irradiation not under control (design dependant)</li> <li>• SEU is an issue</li> </ul>	<ul style="list-style-type: none"> <li>• All aspects of "analogue" functions are affected by radiation : noise, offsets, stability, BW, operating point</li> <li>• Control over biasing voltages or currents (when possible) allows some compensation of radiation effects</li> <li>• SEU (generally) not an issue</li> </ul>

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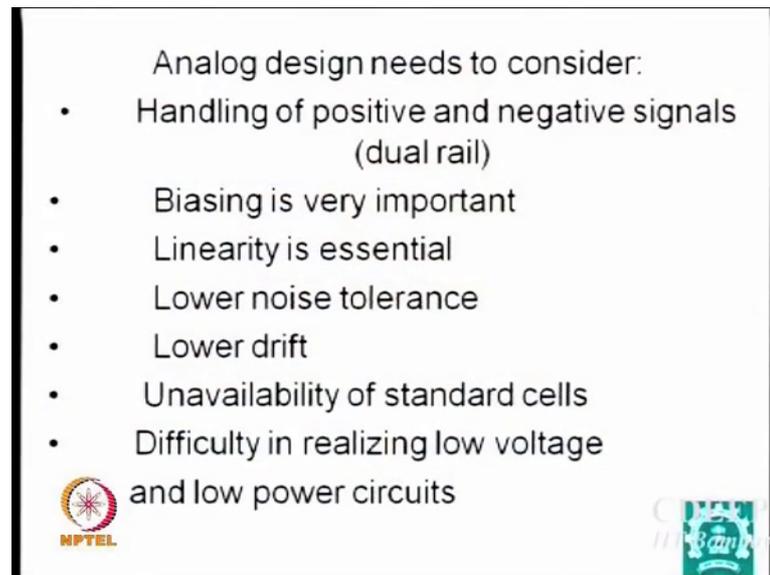
There are issues right now which I worked many years ago and again at the so, what is the solar cell center people are now looking into for solar cell as well as a electronics. There is a problem of natural radiation falling on the circuit. And particularly if you are a satellite based circuits, intense radiation is there.

So, if you see a 2 comparison for radiation purpose, they were a huge threshold shapes, there is a mobility degradation and therefore, speed varies changes much more there can be huge power consumption change after before and after irradiation. And there is what we call single event of sent due to alpha particle hits. If you look at analog now this failing, you know analog Gue, this is a British. So, analog functions are affected by. Here only small amount here everything is affected. So, if you have a analog block and you have opamp circuit sitting on and you are a satellite it will fail faster, that is it. Changes

operating point changes bandwidth changes gain change offsets change stability what not.

Then it also control over biasing voltages are current when possible allows some compensation of radiation. You can actually play with band gap references, and feedback paths to compensate them; which is not possible in the digital. So, some advantage some disadvantage. ACU is certainly not important issue.

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Analog design needs to consider:

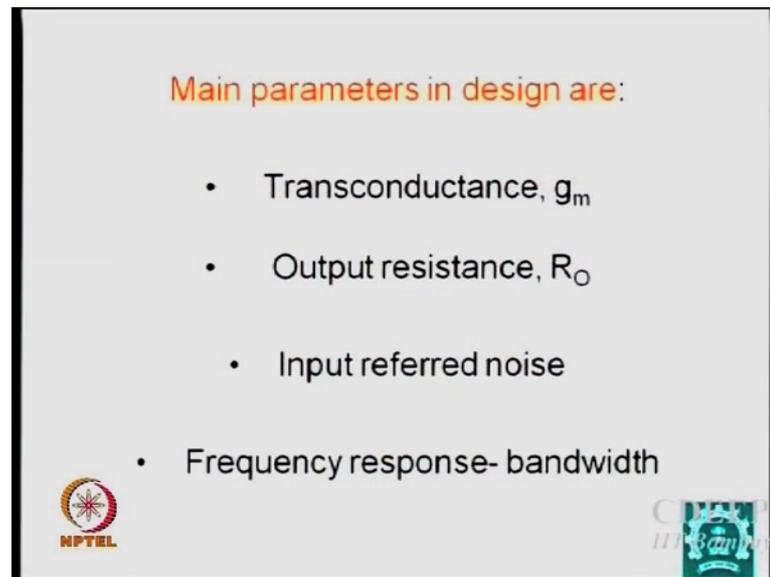
- Handling of positive and negative signals (dual rail)
- Biasing is very important
- Linearity is essential
- Lower noise tolerance
- Lower drift
- Unavailability of standard cells
- Difficulty in realizing low voltage and low power circuits

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This figure is not here we will come back to it later. So, basically what is analog circuit design has needs to consider? In case of analog positive and negative signals both are required because generally it is a  $V_{dd}$  minus  $V_{dd}$  dual rails. Biasing is very important just now I showed, within the gain range only you can keep the device.

So, if you shift out there is no gain for you. Linearity is the essential gain has to be constant. So, you are looking for that is why they are called linear circuits because they are constant gains. We want in general any circuit, but analog more less prone to noise because otherwise noise will supersede everything. You want smaller change in parameters. It is called grips. The problem as I say is there are no standard sets available blocks available we can use. So, you may have to either create your own, and reuse it, or design every time. Then very difficult right now is to design low voltage circuits, and therefore, do power circuits or maybe low energy circuits.

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Main parameters in design are:

- Transconductance,  $g_m$
- Output resistance,  $R_O$
- Input referred noise
- Frequency response- bandwidth

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There are 3 parameters which you shall work in analog design, these are our what you should say bread butter parameters. The transconductance  $g_m$  output resistance  $R_O$ , and the third and the most important input referred noise. That is the 3 parameters important as far as the gain side is concerned, outputs are concerned. And finally, for all analog circuit we are worried about bandwidths, which is our frequencies. So, how do we tackle each of them and still do not lose on others is what the game is all about designs. So, we stop here today. We will come back next time.