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HDMI 2.0 and the Push for 4k

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The basic AV law: All AV technologies are designed for human hearing and vision.

Tip: This whitepaper contains some technical discussions. If you do not want to read them, just skip them and only read the section titles in bold fonts.

The "post" HD era?

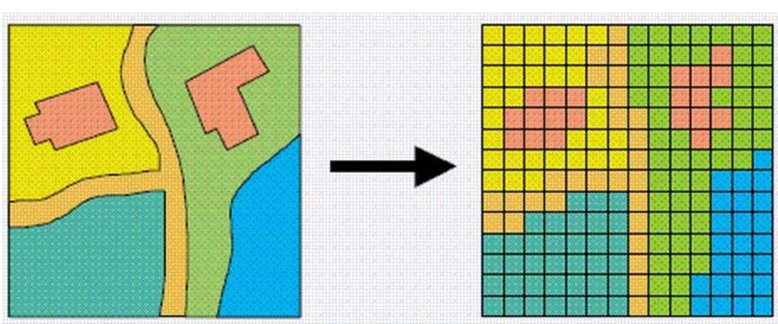
The good old analog color TV had served us well for over 50 years. In 1998, the US started the first HDTV broadcast. 15 years later, the US HDTV adoption rate is 75%. The rest of the world is still catching up.

Just before we complete our transition to HD worldwide, the 4k Ultra HD (or UHD) is here already. CEA defined the UHD term on 10/17/2012; HDMI announced the version 2.0 specs on 9/4/2013; ATSC committee published the proposals for the ATSC 3.0 TV transmission system on 10/3/2013.

What's 4k? Who needs it? What to expect? How to adopt it? We'll analyze these questions from the supply (manufacturers and technologies), demand (customers) and ecosystem aspects.

The basics of digital picture and video

A 35 mm file camera captures the whole frame of picture onto one film. The 35 mm movie camera captures 24 frames of pictures per second. These films do not have pixel structure and thus no pixel count. In theory, the resolution can be infinity. In practice, the lens size and focus precision, and the film particle size can limit the resolution. Research has found that the 35 mm film has an equivalent image resolution to a digital camera with 4 to 16 MP (mega pixels).



The digital camera breaks up the image projected on the image sensors into horizontal and vertical rolls, or raster. The smallest element is called a pixel. The total number of pixels is calculated in this formula:

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P = H * V

P is the total number of pixels; H is the total number of pixels in a horizontal line; V is the total number of pixels in a vertical line.

The uncompressed image file size is calculated using this formula:

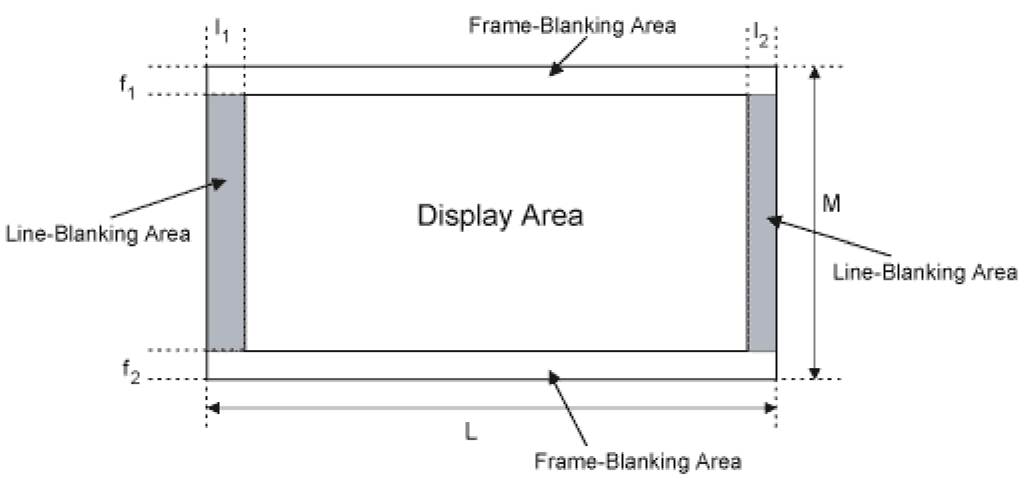
S = H * V * B /8

S is the uncompressed file size in Bytes. The B is the bit depth, or the number of bits used in digitizing each pixel. Since 1 Byte = 8 bits, the number needs to be divided by 8 at the end.

Here are some examples of the pixel counts and file sizes of the most common formats:

Format	H (pixels)	V (pixels)	P (total pixels)	B (bit depth)	S (file size)
XGA	1024	768	0.8 MP	24 bits	2.4 MB
WXGA	1280	768	1.0 MP	24 bits	2.9 MB
1080p	1920	1080	2.1 MP	24 bits	6.2 MB
4k	4096	2160	8.8 MP	24 bits	26.5 MB
Nokia 1020	7712	5360	41 MP	24 bits	124 MB

The digital video basically is many frames of digital images collected together with audio and other data added. One important difference is that the video frame has blanking areas both at the left and right (horizontal blanking) and top and bottom (vertical blanking). The blanking was initially designed for CRT monitors and cameras to allow the electronic beam retrace back after it finishes scanning one line or one frame; but in digital video, the blanking is retained to insert other auxiliary data.



The total data rate (bps or bits per second) of a video signal is calculated using this formula:

D = (H/k1) * (V/k2) * R * B /k3

D is the data rate. H, V, and B were explained in last page. R is the refresh rate, or the number of frames per second (Note it's not always the vertical frequency. If the video is in progressive mode, these two are the same. If the video is in interlaced mode, then the refresh rate is half of the vertical frequency). The k1, k2 and k3 are 3 factors. k1 is the total number of active horizontal pixels divided by the total number of horizontal pixels. k2 is the total number of active vertical pixels divided by the total number of vertical pixels. k3 is the total number of bits of video data divided by the total of all data. These factors vary from format to format, but they are all close to 0.9 (in other words, about 90% of the horizontal pixels are visible, about 90% of the lines are visible, and about 90% of the data is video). For simplified calculations, we can use 0.9 for each of these factors.

The uncompressed video file size is calculated using this formula:

Sv = (H/k1) * (V/k2) * R * B /k3 * T /8

Sv is the video file size in Bytes. T is the total duration of the video in seconds. The rest of the symbols were discussed earlier in this paper.

Now let's see the data rates of several common video formats and the uncompressed file size for a 2 hour movie of each format.

Format	H	V	R (refresh rate)	B (bit depth)	D (data rate)	T (time duration)	Sv (file size)
YouTube HQ	480	360	30 fps	24 bits	171 Mbps	2 hr	154 GB
720p	1280	720	60 fps	24 bits	1.8 Gbps	2 hr	1.6 TB
1080p 24 Hz	1920	1080	24 fps	24 bits	1.6 Gbps	2 hr	1.5 TB
1080p 60 Hz	1920	1080	60 fps	24 bits	4.1 Gbps	2 hr	3.7 TB
4k 30 Hz	4096	2160	30 fps	24 bits	8.7 Gbps	2 hr	7.9 TB
4k 60 Hz	4096	2160	60 fps	24 bits	17.5 Gbps	2 hr	15.7 TB

The need for compression:

How many times has your Outlook been slowed down because someone sent you emails with 50 MB picture attachments? You should understand the need for compression first hand.

Take a look at this table of digital image file size again; I've added the comparison before and after compression.

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					JPEG compression					
					No			Yes		
Format	H (pixels)	V (pixels)	P (total pixels)	B (bit depth)	S (file size)	Number of pictures fit in a 4 GB drive	Time to download an email with 10 pictures	S (file size)	Number of pictures fit in a 4 GB drive	Time to download an email with 10 pictures
XGA	1024	768	0.8 MP	24 bits	2.4 MB	1670	24 sec	180 kB	22000	1.8 sec
WXGA	1280	768	1.0 MP	24 bits	2.9 MB	1380	29 sec	220 kB	18000	2.2 sec
1080p	1920	1080	2.1 MP	24 bits	6.2 MB	645	62 sec	480 kB	8000	4.8 sec
4k	4096	2160	8.8 MP	24 bits	26.5 MB	150	5 min	2 MB	2000	20 sec
Nokia 1020	7712	5360	41 MP	24 bits	124 MB	32	21 min	9 MB	420	90 sec

Some company email servers still limit the email size to 10 MB; you can see it's not possible to send any 8 MP uncompressed pictures. Also, for a smart phone with 4 GB storage allocated for pictures, it can only hold 150 uncompressed pictures.

The JPEG compression can achieve an average 13:1 compression without major visible artifacts.

The need for video compression is not a convenient factor, rather it is a necessity. Take a look at this video file size table again with the comparison to the speed current infrastructure can handle:

					MPEG-2 compression				
					No	Yes		No	Yes
Format	H	V	R (refresh rate)	B (bit depth)	D (data rate)	D (data rate)	T (time duration)	Sv (file size)	Sv (file size)
YouTube HQ	480	360	30 fps	24 bits	171 Mbps	1.7 Mbps	2 hr	154 GB	1.5 GB
720p	1280	720	60 fps	24 bits	1.8 Gbps	18 Mbps	2 hr	1.6 TB	16 GB
1080p 24 Hz	1920	1080	24 fps	24 bits	1.6 Gbps	16 Mbps	2 hr	1.5 TB	15 GB
1080p 60 Hz	1920	1080	60 fps	24 bits	4.1 Gbps	41 Mbps	2 hr	3.7 TB	37 GB
4k 30 Hz	4096	2160	30 fps	24 bits	8.7 Gbps	87 Mbps	2 hr	7.9 TB	79 GB
4k 60 Hz	4096	2160	60 fps	24 bits	17.5 Gbps	175 Mbps	2 hr	15.7 TB	157 GB

Media	Data rate
DSL internet	5 Mbps
4G LTE	15 Mbps
ATSC broadcast	19 Mbps
Blu-ray disc	36 Mbps
Fiber internet	100 Mbps

You can see that without compression, we don't have any media to transmit or store even a low quality YouTube video.

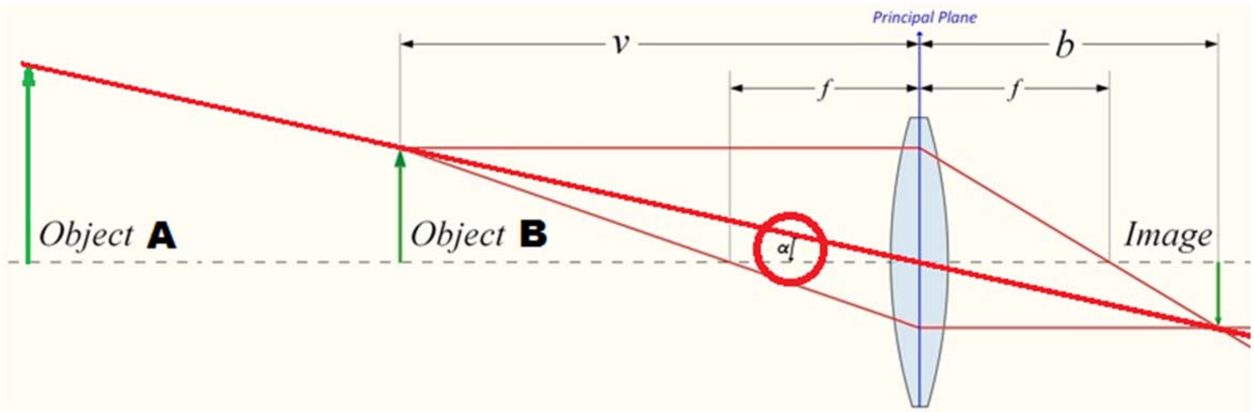
The MPEG-2's amazing 100:1 compression ratio was the key innovation that started the digital revolution in 1990 during the development of the US HDTV (ATSC), and enabled so many other digital technologies like the DVD, Blu-ray, DBS satellite, YouTube, Netflix, mp3, Dolby Digital, iTunes, etc.

How much resolution can the human eye see?

Keep in mind that all technologies we invented are for human usage; so they all must meet a human's needs or capabilities, not a machine's.

The human eye has a lens, an iris, and a sensor, just like a camera. Whether a human can see an object or not depends primarily on the size AND the distance of the object, and other conditions like the lighting, color, contrast, etc.

Take a look at the illustration below. Object A and B both project an image of the same size on the human eye's retina. So our eyes actually cannot tell how big or small an object is; they can only tell how big the entry angle "α" (in the red circle) is.



The smallest entry angle an average human eye can see is about 1/60 of a degree, or an arcsecond. In other words, the human eye's angular resolution is one arcsecond.

Critical viewing distance

As we discussed earlier, the digital image or video is composed with millions of tiny pixels. When the viewer is standing close enough to the display, he/she should be able to see the pixel structure of the digital image or video. This is not intended because we want the pixel structure to disappear.

Now the viewer backs up slowly from the display until the pixel structure is invisible to him/her. This viewing distance is called critical or optimum viewing distance. Anywhere closer than this distance, the pixel structure is visible; anywhere further away from this distance, the finest details would not be visible (or the display resolution would be wasted).

Based on the human eye's angular resolution, we can easily calculate one of these 3 factors: critical viewing distance, display resolution, display size, when we know the other 2. The formula is:

$$L = \frac{Sd}{\tan 1' * \sqrt{H^2+V^2}} = \frac{Sd}{0.000291 * \sqrt{H^2+V^2}}$$

L is the critical viewing distance; Sd is the display diagonal size; H is the number of horizontal pixels; V is the number of vertical pixels. The unit for L and Sd is the same; if one in inches, the other is too. If one in meters, the other is too.

With this formula, let's see the calculated numbers for several typical applications:

Application	Format	H (pixels)	V (pixels)	Sd screen size (inch)	L viewing distance (feet)	L viewing distance (m)	Proper or not
Classroom projector	XGA	1024	768	100	22	6.8	Yes
Laptop	WXGA	1280	768	15	2.9	0.9	Yes
Smartphone	iPhone 5s	1136	640	4	0.9	0.3	Yes
Bedroom TV	720p	1280	720	40	8	2.4	Yes
Living room TV	1080p	1920	1080	55	7	2.2	Yes
Living room TV	4k	4096	2160	65	4	1.2	No
Movie theater	4k	4096	2160	56 feet	42	13	Yes

HDMI 2.0 specs, what's new?

- Increased the max data rate from 10.2 to 18 Gbps
- 4K@50/60, (2160p), which is 4 times the clarity of 1080p/60 video resolution
- Up to 32 audio channels for a multi-dimensional immersive audio experience
- Up to 1536kHz audio sample frequency for the highest audio fidelity
- Simultaneous delivery of dual video streams to multiple users on the same screen
- Simultaneous delivery of multi-stream audio to multiple users (up to 4)
- Support for the wide angle theatrical 21:9 video aspect ratio
- Dynamic synchronization of video and audio streams
- CEC extensions provide expanded command and control of consumer electronics devices through a single control point

What challenges does the higher data rate bring to the electronics?
Lu's law No. 1

We must have noticed that the PC manufacturers have added big heat sinks and fans to the CPU starting with the Intel's Pentium; and since then the desktops and laptops have been running hotter and hotter. Here's the reason behind it:

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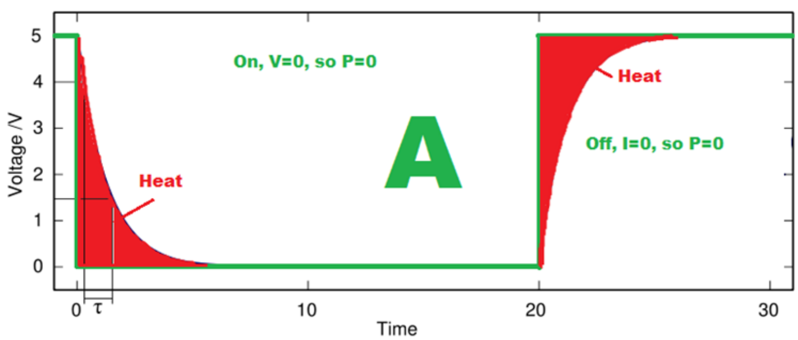
All modern electronics are made of semiconductors. Most semiconductors are formed by many PN junctions. In digital electronics, the signal is either hi (1) or low (0), which means the PN junctions work in the Switch mode. The illustration shows the voltage of a PN junction over time.

In an ideal situation, the PN junction voltage over time should reassemble a perfect square wave, just like the digital signal, in the green line show in the illustration. With the perfect square wave, the PN junction is either fully "on", or fully "off", like a switch. The heat generated at the PN junction is calculated in this formula:



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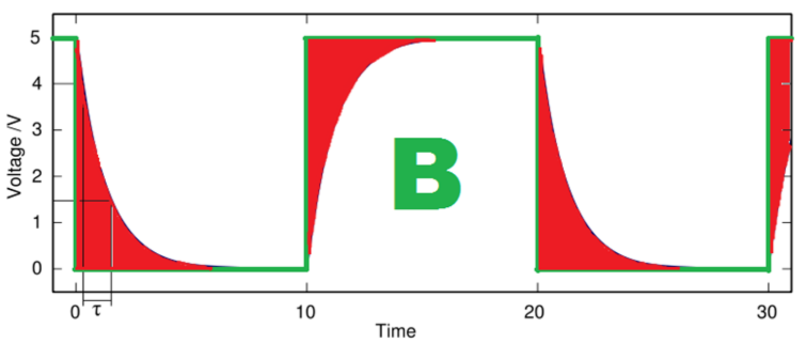


P = V * I

P is the power that generates heat, V is the voltage across the PN junction and A is the current going through the PN junction.

In "on" mode, V = 0; so P = 0 regardless what I is.

In "off" mode, I = 0; so P = 0 regardless what V is.

In other words, the perfect PN junction working in switch mode would never generate any heat.

But nothing is perfect. In reality, there's capacitance across the P/N junction, so the voltage cannot instantly change from hi to low or from low to hi; it will gradually change, like the border of the red area. Now we have a problem. In the red area, neither V nor I is zero, thus the PN junction will consume power and generate heat.

Now compare chart A and B. It's the same PN junction; the only difference is the signal clock frequency in chart B is twice that of in A. In chart A, the red area accounts for about ¼ of the unit interval (the total duration of one bit, from 0 to 20 on time axis); in other words, the PN junction generates heat in ¼ of the time period. In chart B, the red area remains the same, but the signal unit interval (from 0 to 10 on time axis) is cut in half. Now the red area accounts for ½ of the unit interval. In other words, the PN junction generates heats in ½ of the time period.

This leads to the **Lu's law No. 1:**

When all else are equal, the semiconductors generate twice the heat when signal data rate doubles.

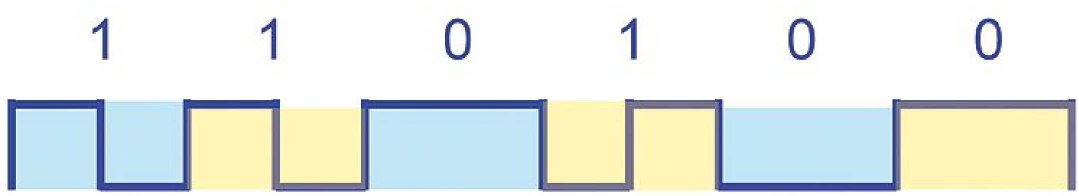
To increase the data rate, the semiconductor makers must deal with this heat problem by using more precise processes and expensive materials to reduce the PN junction capacitance. These lead to higher costs. Please take a look at the costs of SFP (Small Form-factor Pluggable fiber transmitter and receiver) at different data rates:

Data rate (Gbps)	Unit price (USD)
4	$ 35
10	$ 165
14	$ 231

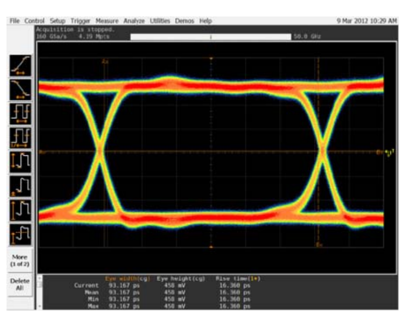
You can see the significant cost increases when the data rate is higher.

What challenges does the higher data rate bring to the cables?
Lu's law No. 2

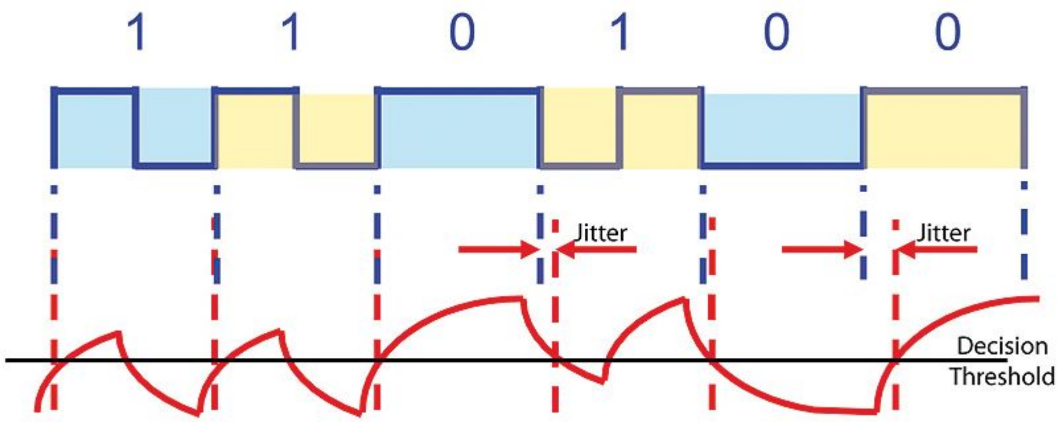
All digital signals are square waves representing many "0"s and "1"s.



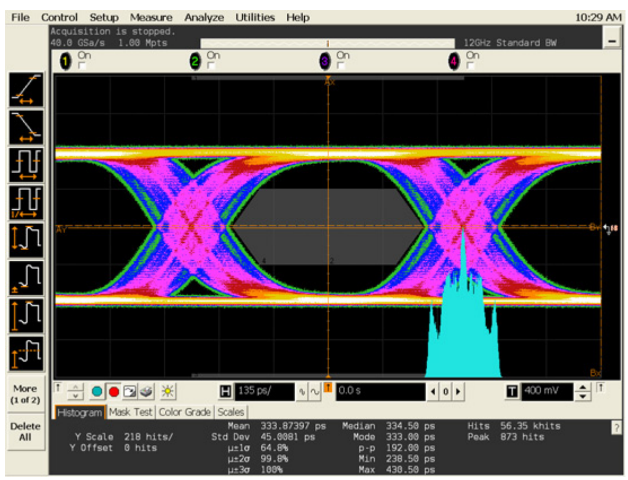
On an oscilloscope, these "0"s and "1"s will overlap with each other, and form the "eye pattern".



The images we show above are the “perfect” signals. When the digital signal travels through a passive cable, the capacitance of the cable will cause the square wave to become the curved charge and discharge patterns:

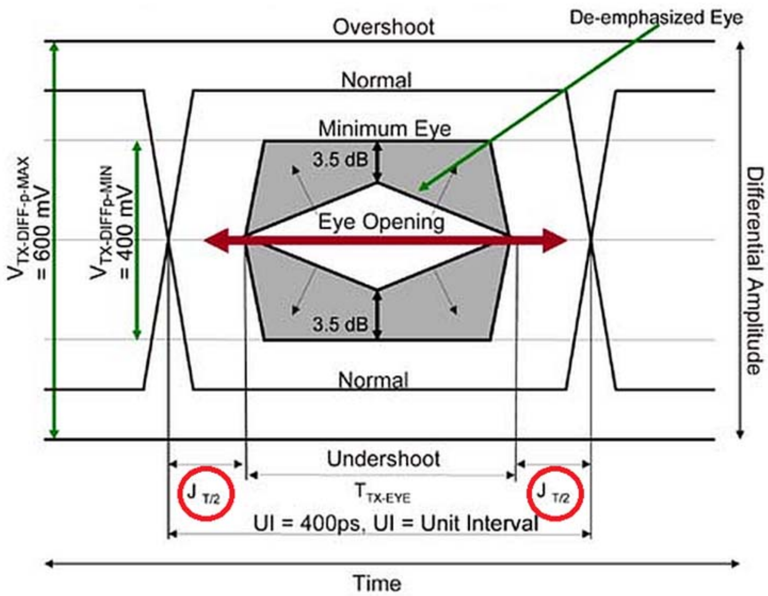


The receiving electronics has a threshold voltage; the signal voltage lower than that is treated as a logic low and the one higher than that is treated as a logic high. Because the capacitance charging and discharging patterns move the voltage up or down, the receiver would judge the high to low or low to high edge in different timing. This timing variation is called a “jitter”. See the jitters in the eye pattern scope screen:



You can see the sides of the eyes become much fatter. When the fat eye sides touch the diamond shape inside the eye, the signal is not recoverable by the receiver anymore because the receiver cannot distinguish whether the bit it receives is from the previous clock cycle or the next clock cycle.

Take a look at the eye pattern illustration below:



The UI is the Unit Interval, the duration of one bit. The J is jitter time, shown on both left and right sides in red circles. When the total jitter time to UI duration ratio is equal to or greater than 0.3, the signal is lost. This is called a critical jitter ratio.

When the signal data rate doubles, the UI is cut in half. If the cable remains the same, the jitter time is the same and the jitter to UI ratio doubles. This would certainly make many cables not work anymore. To make the cable work again, we must cut the cable length in half in order to cut the capacitance and jitter in half, to maintain the same critical jitter ratio. This leads to the **Lu's Law No. 2**:

When all else are equal, the passive cable's maximum usable length is cut in half (for the same critical jitter ratio) when the signal data rate doubles.

Keep in mind that this law applies to passive metal conductor cables as is.

For the active cables, the EQ or Tx/RX ICs follow Lu's Law No. 1, and the cables in between follows Lu's Law No. 2.

For the fiber cables, the Tx/Rx ICs still follow the Lu's Law No. 1; however the optical fiber in between does not follow Lu's Law No. 2 because the fiber has abundantly wide bandwidth.

Moore's laws and the manufacturers' efforts to maintain ASP

In 1965, Intel cofounder Gordon Moore predicted that the number of transistors on integrated circuits doubles approximately every two years (The other Intel executive David House predicted the period to be 18 months).

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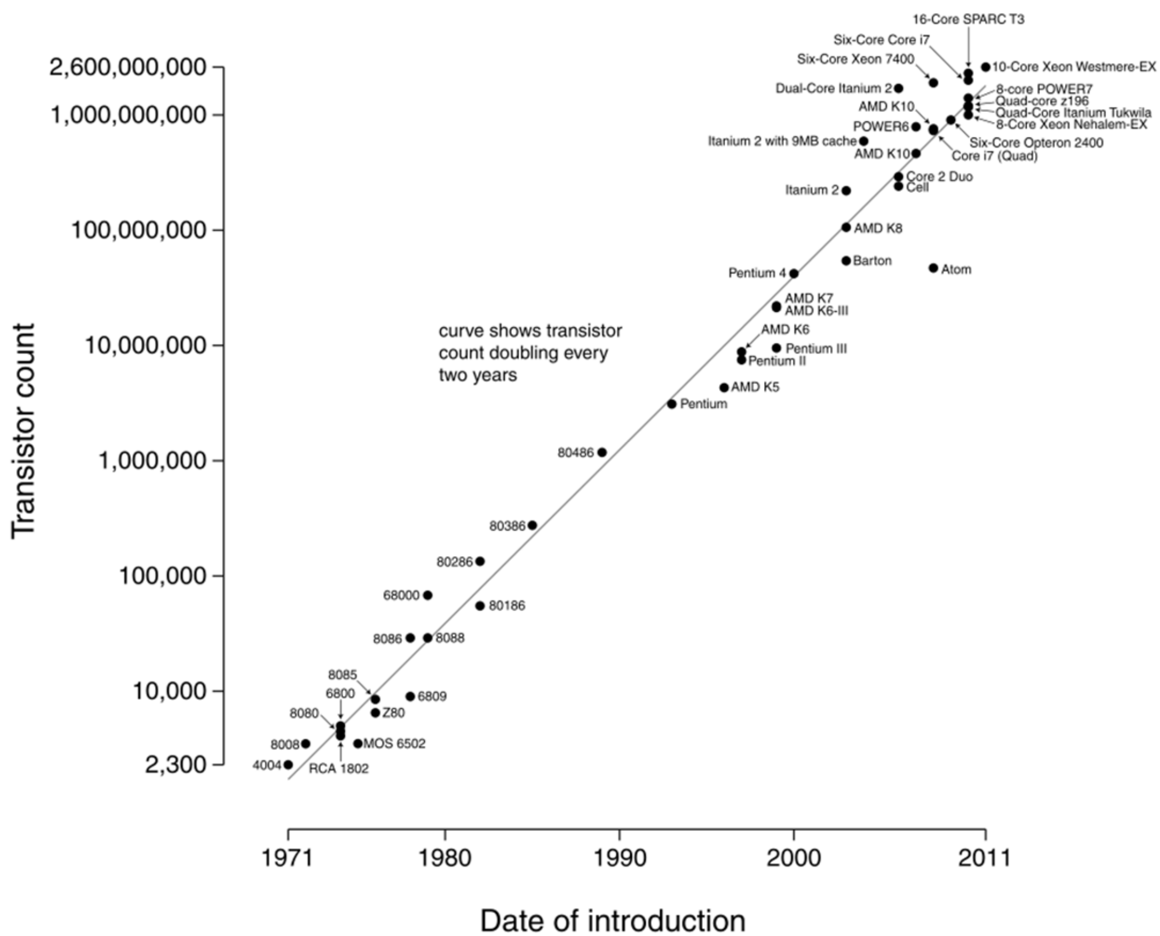
Microprocessor Transistor Counts 1971-2011 & Moore's Law



The later history proved the amazing accuracy of the Moore's prediction back in 1965. In the 40 years from 1971 to 2011, the number of transistors in CPUs grew 1 million times.

Almost all other products' prices go up slowly each year following the inflation rate. But digital electronics' pricing behaves in the complete opposite way, described in the "2nd Moore's Law".

The 2nd Moore's law predicts the cost per transistor drops in half every 2 years. This is a blessing for the customers and a curse for the manufacturers. A PC worth $2000 in 1971 would cost 0.2 cents in 2011!

If nothing changed, the electronics' ASP (Average Selling Prices) would drop in half every 2 years. To avoid the curse of the 2nd Moore's Law, the manufacturers struggle to come out a brand new technology every two years, so they can bring back the ASP to the same point again.

This behavior is most obvious in the PC industry. Intel has been introducing a new CPU about every 2 years.

The AV industry had been spared by the 2nd Moore's law before we adopted the digital technologies. In one extreme, the speaker design has not been changed for a century and the ASP is still increasing over the years at the rate of inflation. The analog TVs used to be immune to the 2nd Moore's Law until we adopted the digital HDTV in 1998. Since then the gravity of the law pulls the TV prices down quickly too.

Just like the PC makers, the AV makers are forced to introduce new technologies every two years or so. We've seen the HDMI, 720p, 1080p, deep color, DLP, LED, OLED, 3D, now the 4k.

The camera makers are struggling too, just look at the number of pixels rise from less than 1 MP to 41 MP in a few years. The pixels needed to fill a typical laptop or smartphone screen is only about 1 MP. Any pixel count more than that is a waste for screen viewing, which is how we view pictures nowadays anyway.

The manufacturer's push for 4k

The motivation for the manufacturers to push 4k or whatever new technologies is understandable, and often admirable.

As stated in the basic AV law, all AV technologies are designed for human hearing and vision. As long as the technologies are improving towards the human hearing and vision limit, they are considered great revolutions.

Once in a while, when we push the technologies BEYOND the human hearing and vision limit, or BEYOND realistic human need, then they become excessive, and eventually will fail. 3D is a good example.

If the only motivation is for maintaining the ASP, then the golden window for the 4k TVs for home may already be closing. A Chinese TV maker Seiki has already cut the 4k TV prices to be in the same range as the current 1080p TVs, see the picture in next page.

So the manufacturers should not jump onto the 4k bandwagon just for the ASP. It requires a lot of investments and may not get the returns they are hoping for.

The manufacturers need innovations to be successful; but innovations do not mean to simply add more pixels. Apple's success in iPhone was not due to more screen pixels.

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The customer's needs for 4k

There's no doubt that the 4k is needed in applications with big screens and/or screens very close to users, like the digital movie theaters, or the big touch screens in the NCIS.

But for average homes or classrooms, it is not needed. Let me bring up this table again.

Application	Format	H (pixels)	V (pixels)	Sd screen size (inch)	L viewing distance (feet)	L viewing distance (m)	Proper or not
Classroom projector	XGA	1024	768	100	22	6.8	Yes
Laptop	WXGA	1280	768	15	2.9	0.9	Yes
Smartphone	iPhone 5s	1136	640	4	0.9	0.3	Yes
Bedroom TV	720p	1280	720	40	8	2.4	Yes
Living room TV	1080p	1920	1080	55	7	2.2	Yes
Living room TV	4k	4096	2160	65	4	1.2	No
Movie theater	4k	4096	2160	56 feet	42	13	Yes

This table clearly shows where the 4k is needed or not needed. The optimum viewing distance for a 65" 4k TV is only 4' (1.2 m). No one would stand that close to watch such a big screen, and there's not even room for the viewer to sit down.

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The ecosystems for 4k

As we learned, today's electronics are connected to other devices one way or the other. We call this environment an ecosystem.

The 4k TV is nice, but it must get content from somewhere. The content can come from local player like a Blu-ray player, PC, DVR, or from the network via streaming or downloading or broadcasting.

Let's bring up this table one more time:

					MPEG-2 compression				
					No	Yes		No	Yes
Format	**H**	**V**	**R (refresh rate)**	**B (bit depth)**	**D (data rate)**	**D (data rate)**	**T (time duration)**	**Sv (file size)**	**Sv (file size)**
YouTube HQ	480	360	30 fps	24 bits	171 Mbps	1.7 Mbps	2 hr	154 GB	1.5 GB
720p	1280	720	60 fps	24 bits	1.8 Gbps	18 Mbps	2 hr	1.6 TB	16 GB
1080p 24 Hz	1920	1080	24 fps	24 bits	1.6 Gbps	16 Mbps	2 hr	1.5 TB	15 GB
1080p 60 Hz	1920	1080	60 fps	24 bits	4.1 Gbps	41 Mbps	2 hr	3.7 TB	37 GB
4k 30 Hz	4096	2160	30 fps	24 bits	8.7 Gbps	87 Mbps	2 hr	7.9 TB	79 GB
4k 60 Hz	4096	2160	60 fps	24 bits	17.5 Gbps	175 Mbps	2 hr	15.7 TB	157 GB

Media	**Data rate**
DSL internet	5 Mbps
4G LTE	15 Mbps
ATSC broadcast	19 Mbps
Blu-ray disc	36 Mbps
Fiber internet	100 Mbps

Take a look at the last column. The file sizes for the 4k are too big for the existing Blu-ray discs or the hard drives in a PC or DVR. There are no suitable local players for 4k as of now.

On the network based device side, take a look at the 3rd to right column. The bandwidth required for streaming 4k video exceeds almost all the current network speeds. So the only option left would be network download devices that download the contents ahead of viewing. This is not the best way to watch 4k content because most viewers do not want to wait for the download. The only download device available now is the Sony FMP-X1. This $700 device only works for a particular Sony 4k TV, can only be connected to Sony servers, and has very limited movies available for download (see the screenshot from the server on next page). We also

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heard the early adoption of HDCP 2.0 created a lot of compatibility issues.

To adopt 4k, all electronics and cables in a system must be upgraded. **<u>The 4k 60 Hz's data rate is 4 times the 1080p 60 Hz</u>**. Based on the Lu's Law No. 1, **<u>the semiconductors would generate 4 times the heat</u>**, which requires extensive new materials and designs to avoid the extra heat, and will also raise the hardware cost. Based on the Lu's Law No. 2, **<u>the usable max cable length would be cut to ¼ that of the 1080p</u>**. Currently the longest passive HDMI cable that can pass the ATC test is about 33' (10) m long. With 4k 60 Hz, that length is cut to 8' (2.5 m). That would bring a lot of challenges to the system integrators.

Conclusions:

4k brings dramatically improved video quality for the big or close screens that can fully utilize its potential, but also posts major challenges to electronics, cables, networks and storage.

No doubt that the network speed, storage capacity, semiconductor cost and cable limitations will eventually rise to the needs of 4k. That's nice for the applications that really need 4k. For the applications where the 4k's advantage cannot be seen by human vision, it's better to use the increased network speed and storage for many other usages that humans can actually benefit from.

Luckily HDMI 2.0 is backwards compatible. Your current systems will still work as is.