

Reference Material

Background on Digital Media

<http://xiph.org/video/vid1.shtml> <http://xiph.org/video/vid2.shtml>

Excellent Overview of Media Compression at

http://people.xiph.org/~tteribe/pubs/lca2012/auckland/intro_to_video1.pdf ;
<https://www.xiph.org/daala/>

HEVC Information <http://hevc.hhi.fraunhofer.de/>

<http://www.atlanta-smpte.org/HEVC-Tutorial.pdf>

H.264 Information <http://www.itu.int/rec/T-REC-H.264>

Tools : www.ffmpeg.org <http://www.videolan.org/>

VP9 Presentation at Google IO 2013 : <http://www.youtube.com/watch?v=K6JshvbllcM>

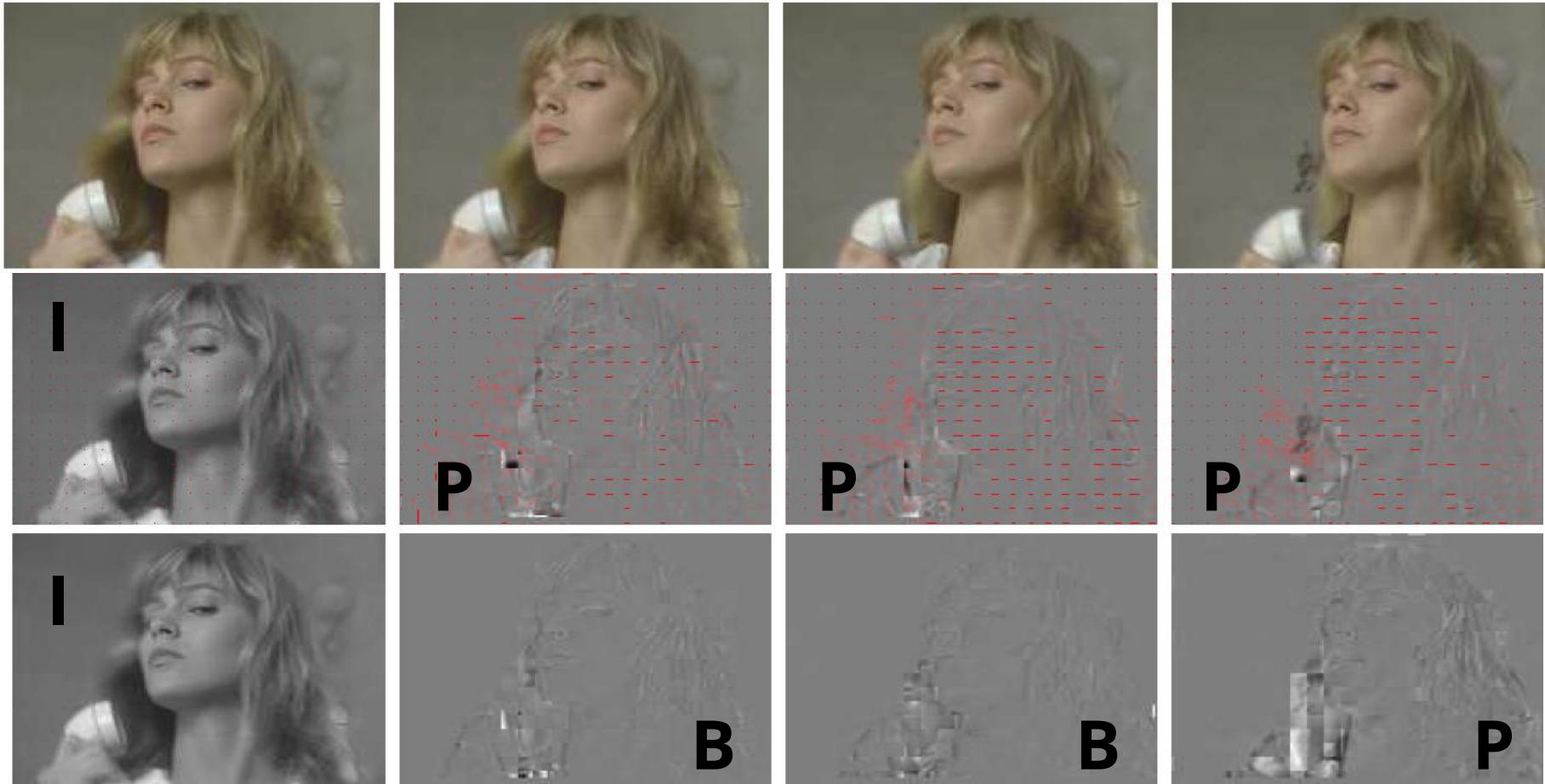
Wikipedia actually quite good on this stuff

Motion Picture Engineering

Prof. A. Kokaram

MODERN VIDEO STANDARDS

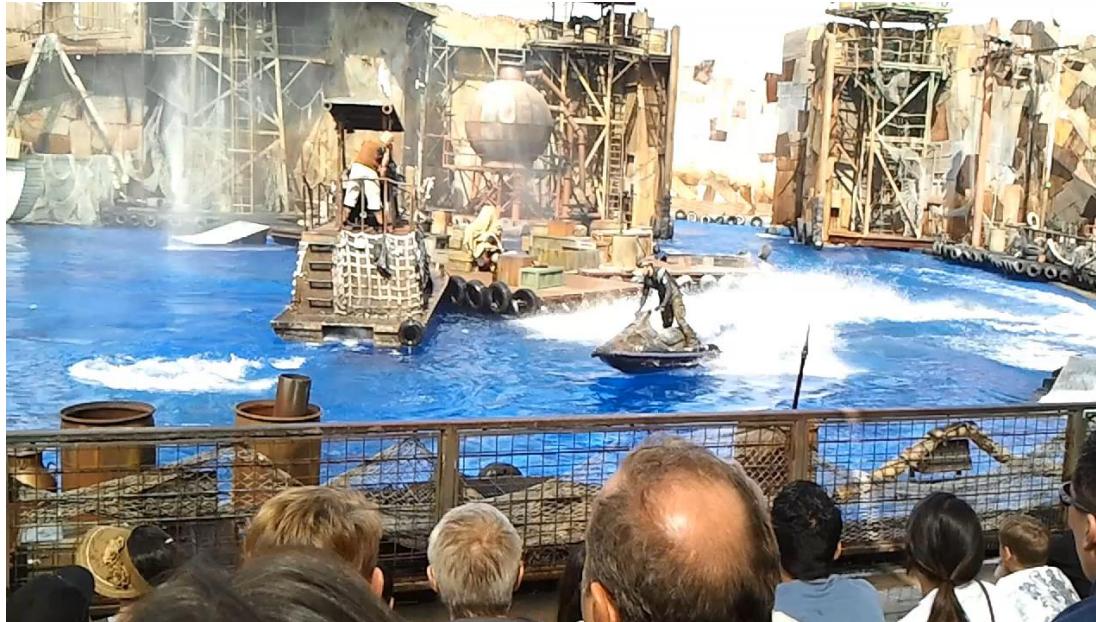
MC Difference Sequence : Smarter Prediction



Examine .MP4 container with H.264 essence

Video recorded and packaged by a Samsung Galaxy SII

(Using www.codecvisa.com for easy to use diagnostic, could also use ffmpeg)



Starting from 1st frame : I, P, P, B, P, B, B, P, P, P, P, P, B, B, P, B, B, P, B, B

I, P, P, B, P, B, B, P, P, P, P, P, P, P, B

Frame 0, Intra-Frame (PTS -0, DTS - 0) : 1.3 Mbits



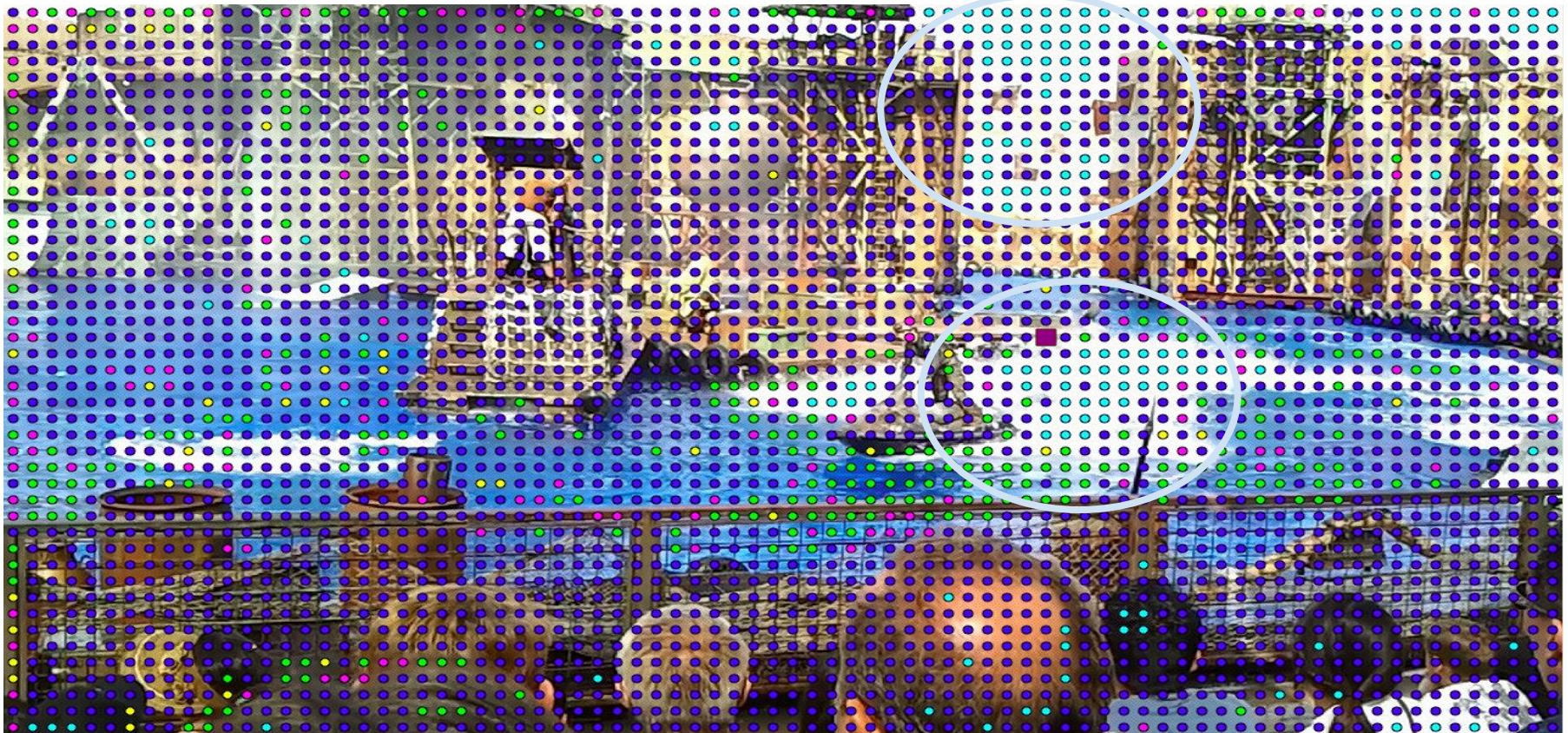
Intra_MB_16x16

Intra_MB_8x8

Intra_MB_4x4

I, P, P, B, P, B, B, P, P, P, P, P, P, B

Frame 1, P-Frame (PTS -1, DTS - 1) : 0.6 MBits



Intra_MB_16x16 Intra_MB_8x8 Intra_MB_4x4 P_MB_16x16 (8) P_MB_Skip

I, P, P, B, P, B, B, P, P, P, P, P, P, P, B

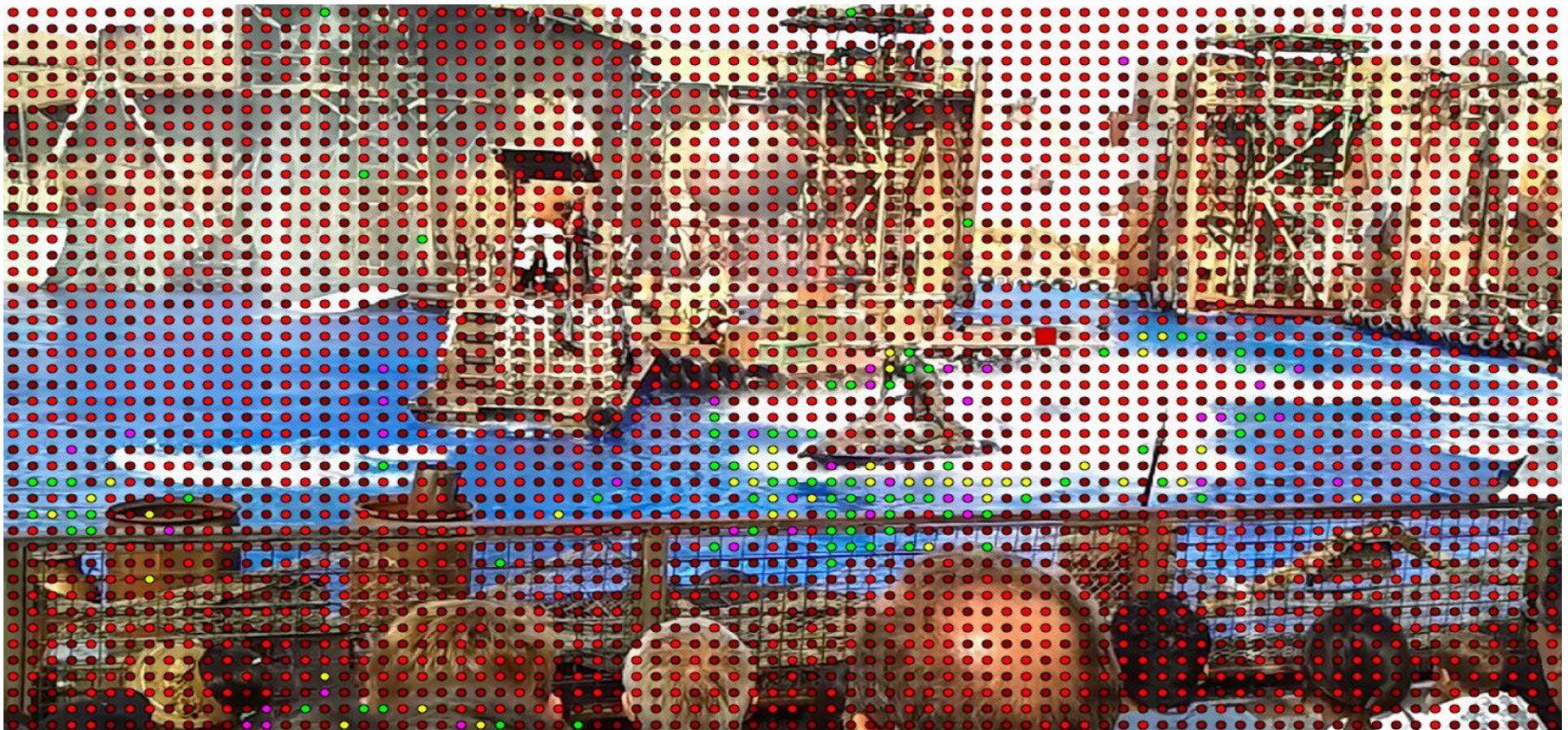
Frame 1 Motion, P-Frame (PTS -1, DTS - 1)



Intra_MB_16x16 Intra_MB_8x8 Intra_MB_4x4 P_MB_16x16 (8) P_MB_Skip

I, P, P, B, P, B, B, P, P, P, P, P, P, P, B

Frame 3, B-Frame (PTS -3, DTS - 4) : 0.2 Mbits



[Pink Box] Intra_MB_16x16 [Yellow Box] Intra_MB_8x8 [Green Box] Intra_MB_4x4 [Dark Red Box] B_MB_16x16 (8) [Red Box] B_MB_Skip

I, P, P, B, P, B, B, P, P, P, P, P, P, P, B

Frame 3, Motion Vectors



Intra_MB_16x16

Intra_MB_8x8

Intra_MB_4x4

B_MB_16x16 (8)

B_MB_Skip

I, P, P, B, P, B, B, P, P, P, P, P, P, P, B

Predicted Frame 3, B-Frame, uses Frames 1 (I) and 4 (P)



■ Intra_MB_16x16

■ Intra_MB_8x8

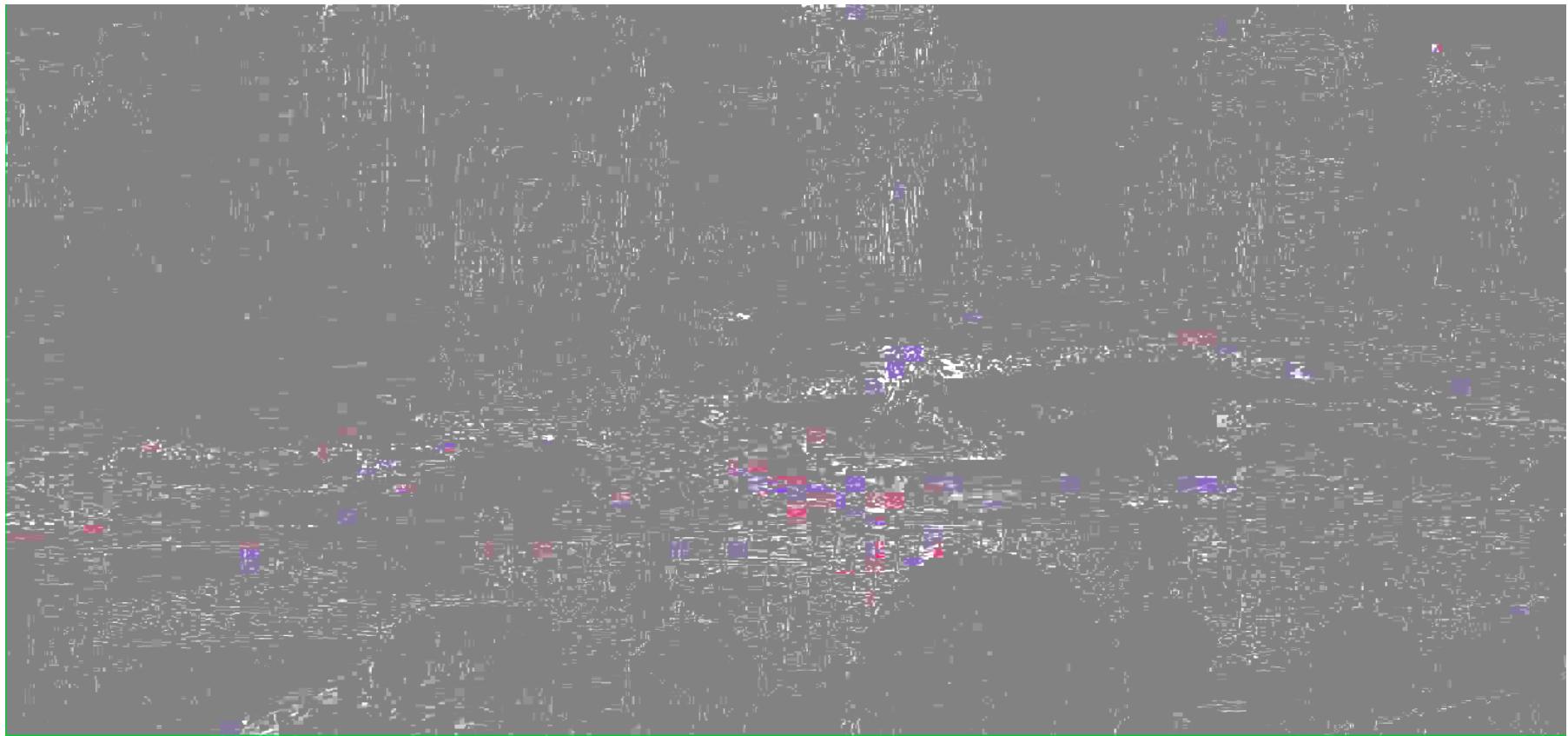
■ Intra_MB_4x4

■ B_MB_16x16 (8)

■ B_MB_Skip

I, P, P, B, P, B, B, P, P, P, P, P, P, P, B

Residual at Frame 3, B-Frame, [i.e. Inverse DCT of MBs]



Intra_MB_16x16

Intra_MB_8x8

Intra_MB_4x4

B_MB_16x16 (8)

B_MB_Skip

I, P, P, B, P, B, B, P, P, P, P, P, P, P, B

Final Decoded Frame 3, B-Frame



[■] Intra_MB_16x16 [■] Intra_MB_8x8 [■] Intra_MB_4x4 [■] B_MB_16x16 (8) [■] B_MB_Skip

I, P, P, B, P, B, B, P, P, P, P, P, P, P, B

Predicted Frame 3, B-Frame, uses Frames 1 (I) and 4 (P)



[■] Intra_MB_16x16 [■] Intra_MB_8x8 [■] Intra_MB_4x4 [■] B_MB_16x16 (8) [■] B_MB_Skip

Predicted Frame 7, P-Frame, uses Frame 4 (P)



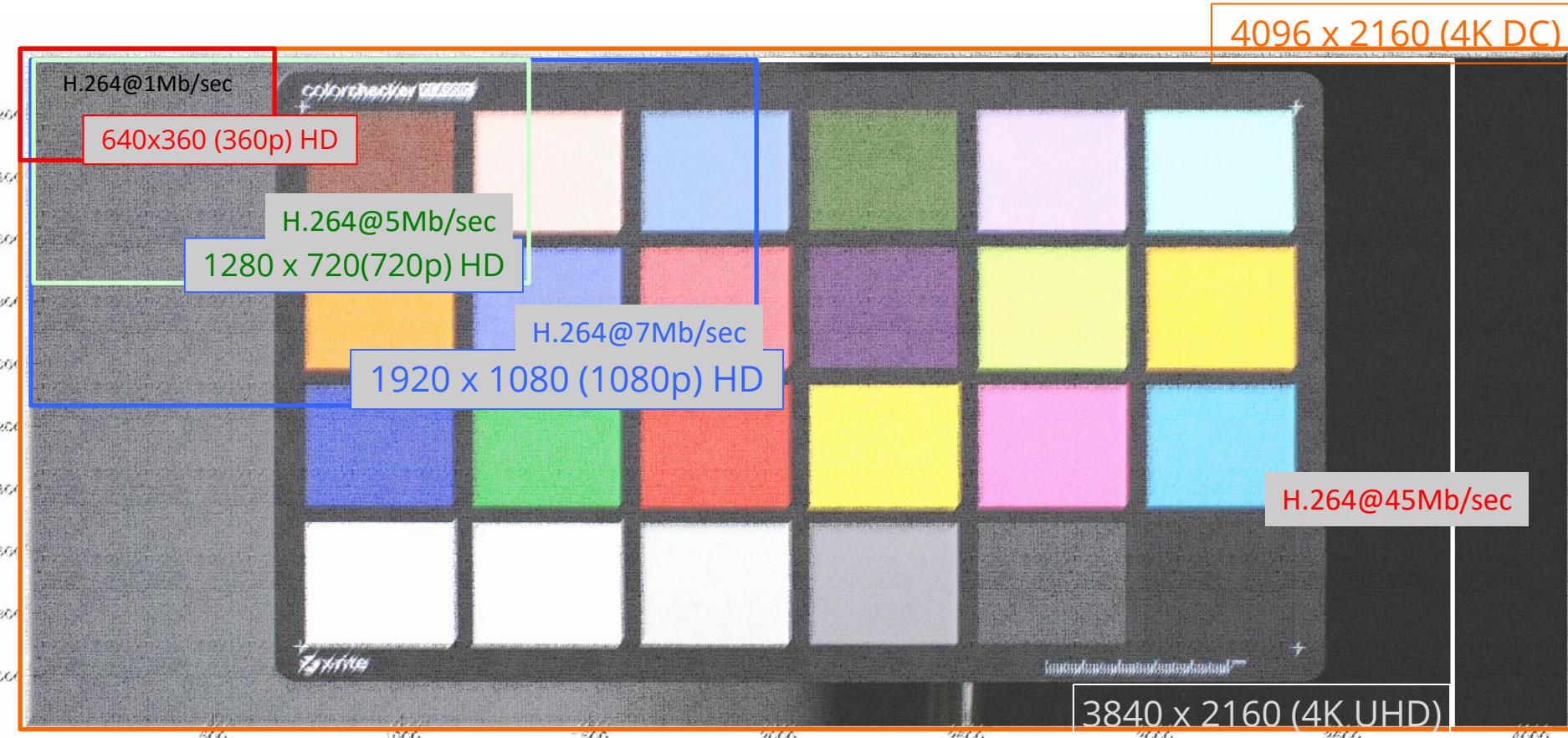
[■] Intra_MB_16x16 [■] Intra_MB_8x8 [■] Intra_MB_4x4 [■] B_MB_16x16 (8) [■] B_MB_Skip

Final Decoded Frame 7, P-Frame, uses Frame 4 (P)



[Intra_MB_16x16] [Intra_MB_8x8] [Intra_MB_4x4] [B_MB_16x16 (8)] [B_MB_Skip]

Picture Formats/Sizes and “rules of thumb bitrates” to remember



VP9 and HEVC

- VP9 from Google Open Web Platform Project WEBM
- Developed by Chrome Media team
- Started in 2011
- Open source project developed entirely in public domain
- Unorganised progress, compression gains measured against test set every day
- Bitstream finalised June 2013
- Launched at Google IO 2013
- *YT streams 4K to an LG 4K TV Set in CES 2014*
- No Royalty payment needed
- Bitstream documented by the code!

Matroska (.mkv)

VP9 Video

Vorbis Audio

- HEVC is latest evolution of H.26x (H.265)
- MPEG Consortium
- Very organised, documents available
- Bitstream documented and available online at ITU
- Highly academic driven. See Special Issue of IEEE CSVT 2012 on HEVC. Also won best paper prize (Wiegand).
- Goal 50% lower bitrate at same quality as H.264
- Draft since 2012, finalised in 2013.
- *Akami/Qualcomm/Elemental Demo HEVC streaming at CES 2014.*

Why the fuss?

- Licensing fees for H.264 and variants are significant and affect the cost of hardware codecs and hence phones
- Streaming media companies also pay licensing for encoding.
- MPEG/ITU : Important “trusted” *international standardisation bodies*. Enabled the underbelly of the digital media marketplace in the late 90’s and since. If MPEG say that a bitstream is like so, then it must be so?
- Google/YT : *A private company* committed to Open Source code. As CPUs get faster and consumer lower power codecs become viable in software. Open source software used by a large community can be more robust and faster than software from a closed community. Google/YT are even releasing *open source hardware IP!*

The News from 2015

<http://youtube-eng.blogspot.ca/2015/04/vp9-faster-better-buffer-free-youtube.html>

MPEG-LA announced HEVC licensing terms in October 2015.

[<http://www.mpeglalicensing.org/main/programs/HEVC/Pages/Agreement.aspx>]

20c per unit over 100K units, max of \$25M/year backdated from 2013!

Conservative 35 Million Iphones sold in 1 Quarter. So Apple already at \$25M Cap.

Scared everybody into looking at VP9 again. Netflix using VP9 for all 480p and below.

MPEG LA's HEVC Licensing Terms Are Flawed, Will Prevent Adoption

There's no reason for Adobe to add HEVC support to Flash, and that keeps HEVC from becoming relevant for general purpose streaming.

By Jan Ozer

For the rest of the June 2014 issue of Streaming Media magazine please [click here](#)



As you might know, MPEG LA announced the licensing terms for HEVC back in January. At the time, I thought, as most observers did, that those terms would provide long-needed certainty. Upon further reflection, I think they're flawed and will delay, if not prevent, the adoption of HEVC in the streaming space. For HEVC to flourish there, MPEG LA needs to dramatically revamp the structure for free players.

A screenshot of a GitHub repository page. The repository is named "Netflix / vp9-dash". The page includes a navigation bar with links for "Code", "Issues (1)", "Pull requests (0)", "Pulse", and "Graphs". Below the navigation, there is a section titled "VP9 ISO-BMFF Packaging Specification and sample files". It shows a commit history with 4 commits, 1 branch, and 0 releases. A dropdown menu indicates the branch is "master". There are buttons for "New pull request", "New file", "Find file", and "HTTPS". Below the commit history, there are sections for "tcase-netflix" (Adding encrypted & unencrypted DASH VP9 samples with key), "DASH-Samples" (Adding encrypted & unencrypted DASH VP9 samples with key), "Downloads" (Draft ISO-BMFF Spec), and a link to "https://github.com/Net".

The Later News

Alliance for Open Media

Announced Sept 2015

<http://aomedia.org/>

THE OPEN AND ROYALTY-FREE FORMAT FOR NEXT-GENERATION
ULTRA HIGH DEFINITION MEDIA



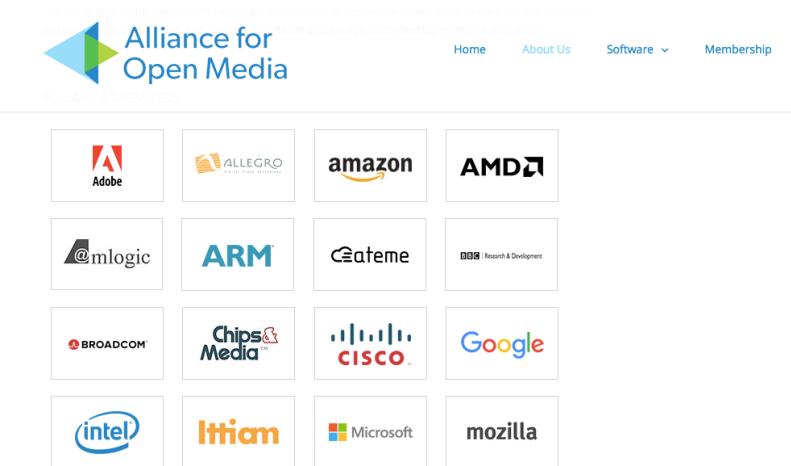
mozilla



NETFLIX

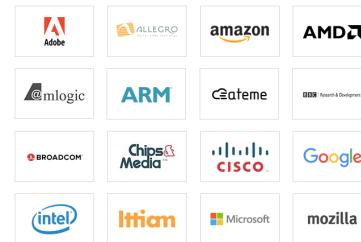
The 2016 News

- 16 companies involved in AOM Codec
- Netflix commits to VP9 (Oct 2016)
- MPEG “Future Video Coding” Launches (H.266)



@Netflix in Los Gatos Nov 2016





The Latest News

- (2020) AV1 Rolls out in Netflix, YouTube
- (2019) AV2 development begins, [MPEG5 Essential Video Coding begins](#)
- (2018) AV1 Bitstream frozen this month?
- (2018) Film grain synthesis is part of the codec .. Required by Netflix.
- (2018) Qualcomm and other hardware manufacturers are not that keen on this extra bit of complexity
- (2017) AOM Codec now called AV1
- (2017) Apple announced that it will commit to HEVC (uh oh)
- (2017) Facebook joined AOM
- See [here](#) for more tension

Wonderful exposition of history of MPEG is here



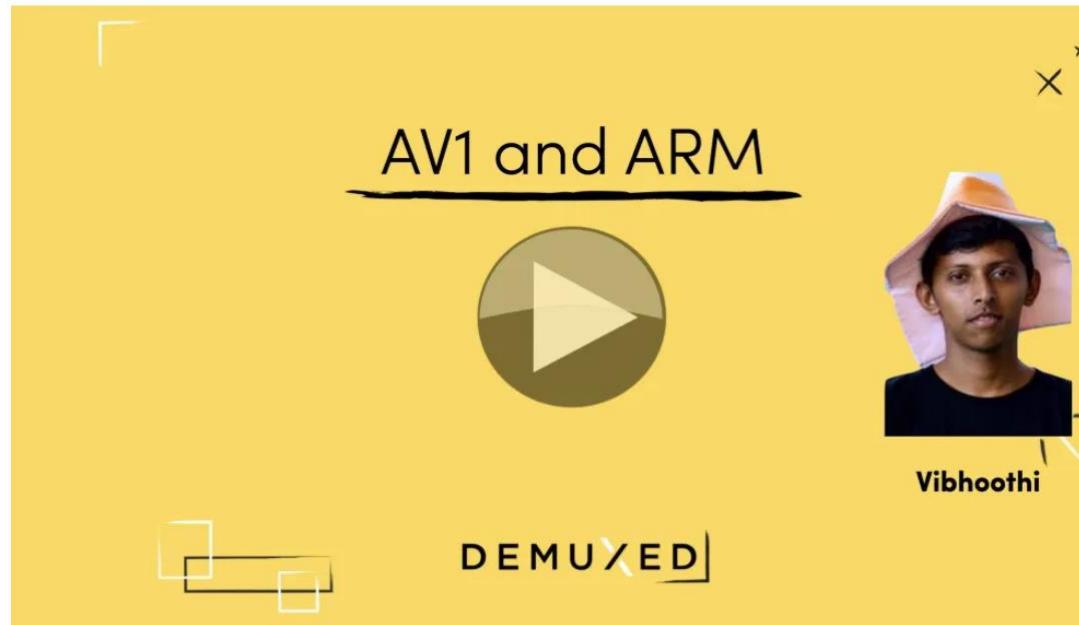
Really Really Latest News

Dav1D AV1 encoder in software available since 2020

See [here](#) for a detailed exposition by Viboothi (Major contributor to the Open Source AV1 initiative)

Video: AV1 and ARM

Posted on 16th March 2021 by Russell Trafford-Jones



AV1's no longer the slow codec it was when it was released. Real-time encodes and decodes are now practical with open-source software implementations called `rav1e` for encoding and `dav1d` for decoding. We've also seen in previous talks the `SVT-AV1` provides real-time encoding and `WebRTC` now has a real-time version with the AV1 codec.

Profiles for VP9/HEVC

VP9

HEVC

4:2:0 Launched 2013

4:2:0 4:2:2 4:4:4

4:2:2 Launched 2015

Main (see next slide)

4:4:4 Launched June 2014

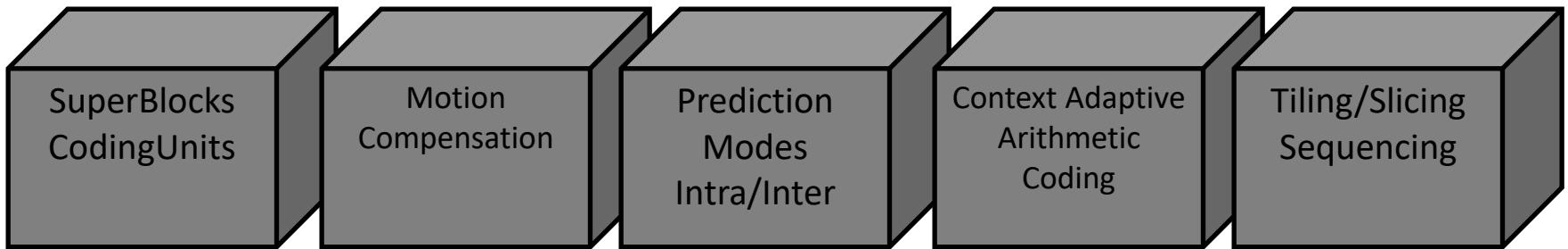
10 bit 12 bits Launched
June 2014

Main 10
10 bit

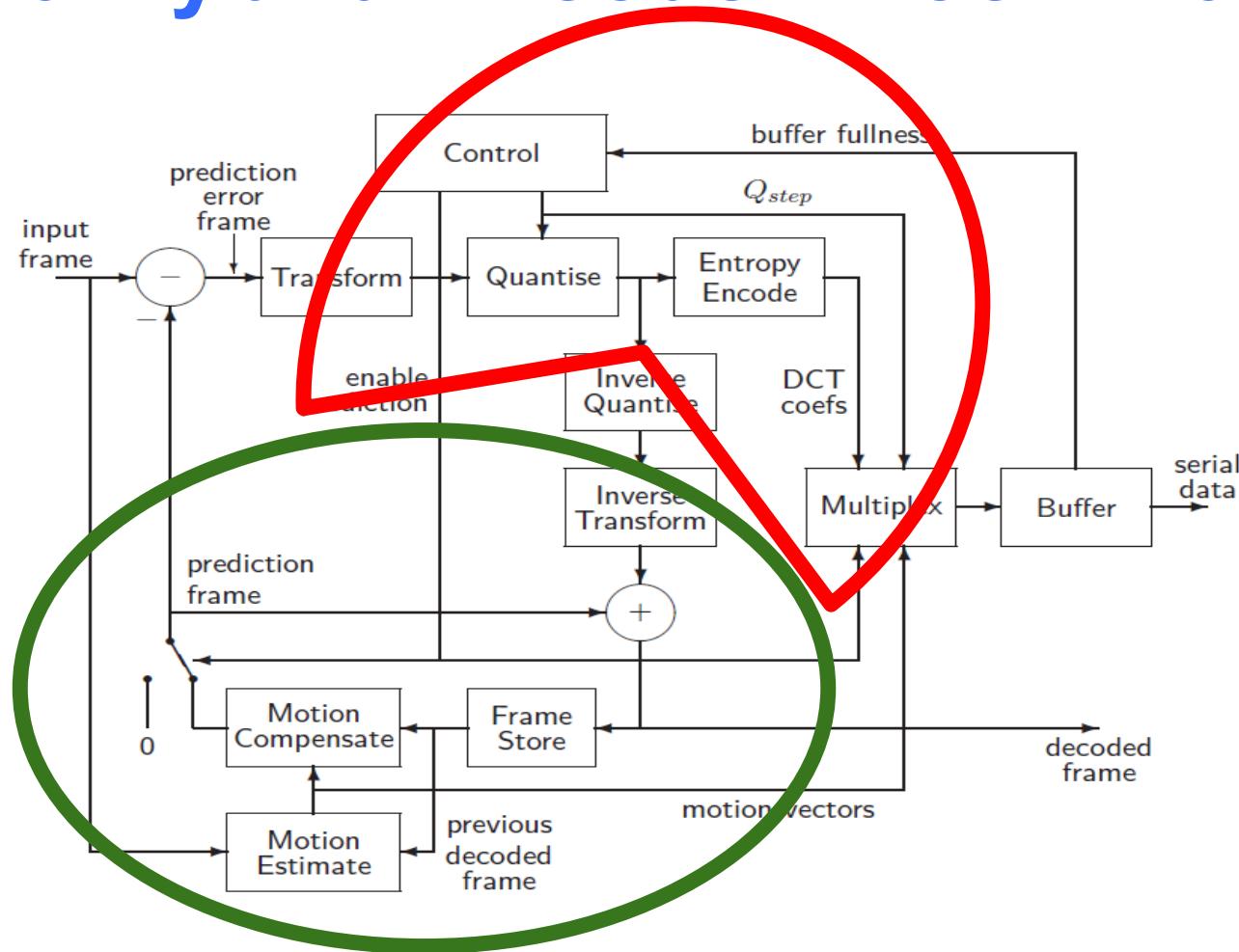
Levels, Tiers for HEVC

Level	Max Luma Picture Size (samples)	Max Luma Sample Rate (samples/s)	Main Tier Max Bit Rate (1000 bits/s)	High Tier Max Bit Rate (1000 bits/s)	Min Comp. Ratio
1	36 864	552 960	128	—	2
2	122 880	3 686 400	1500	—	2
2.1	245 760	7 372 800	3000	—	2
3	552 960	16 588 800	6000	—	2
3.1	983 040	33 177 600	10 000	—	2
4	2 228 224	66 846 720	12 000	30 000	4
4.1	2 228 224	133 693 440	20 000	50 000	4
5	8 912 896	267 386 880	25 000	100 000	6
5.1	8 912 896	534 773 760	40 000	160 000	8
5.2	8 912 896	1 069 547 520	60 000	240 000	8
6	35 651 584	1 069 547 520	60 000	240 000	8
6.1	35 651 584	2 139 095 040	120 000	480 000	8
6.2	35 651 584	4 278 190 080	240 000	800 000	6

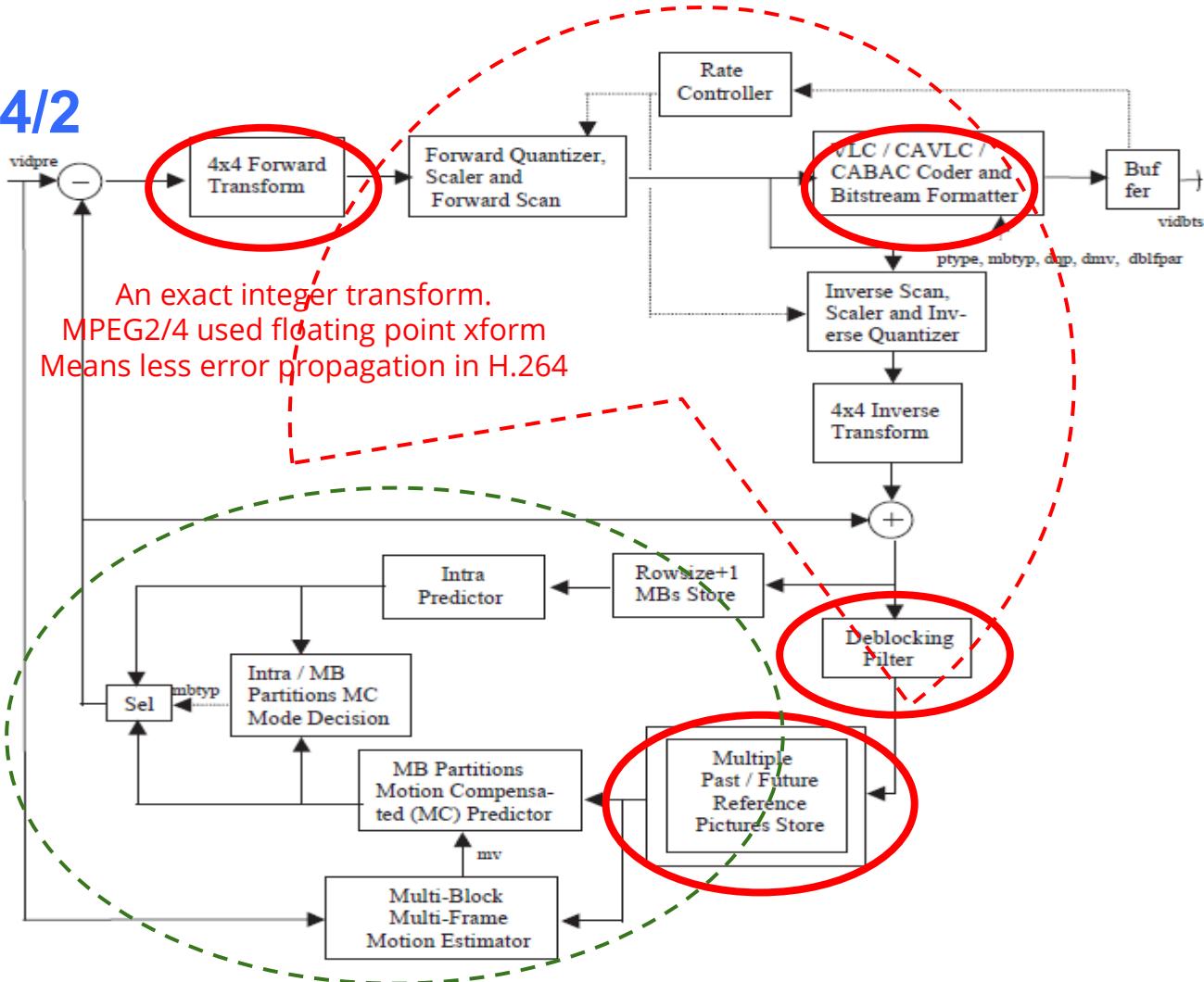
Subset of The New Tools



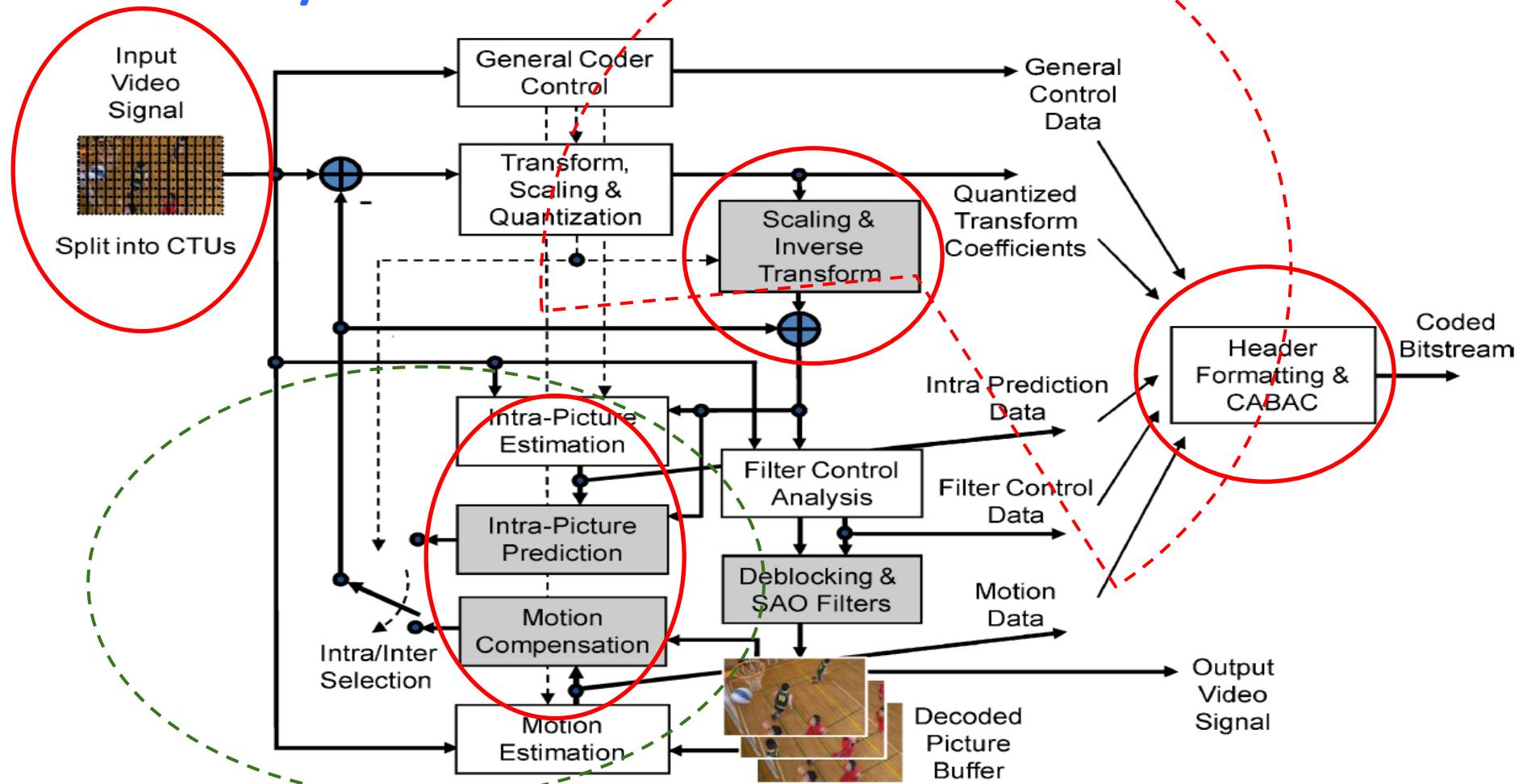
Vanilla Hybrid Encoder Block Diagram



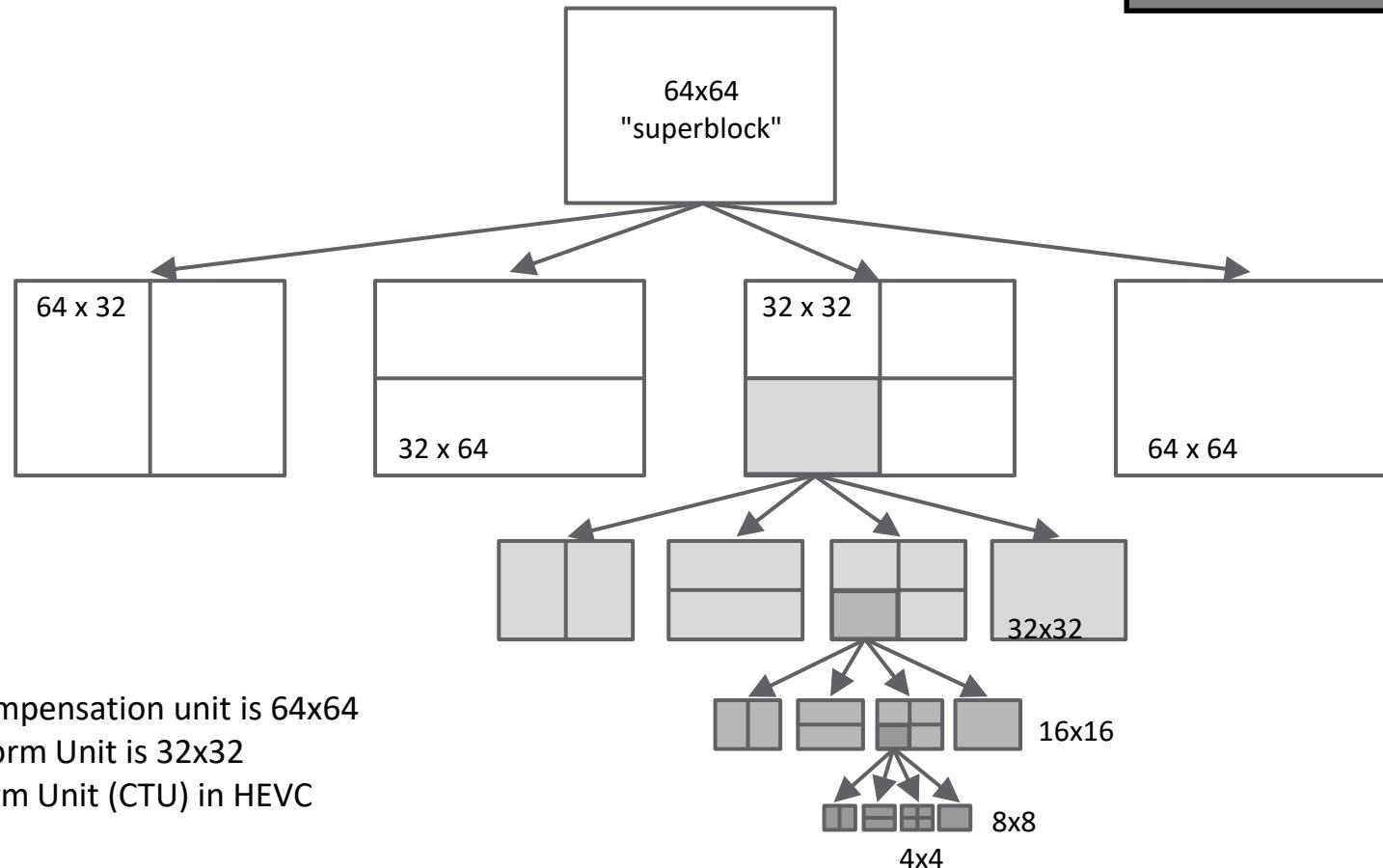
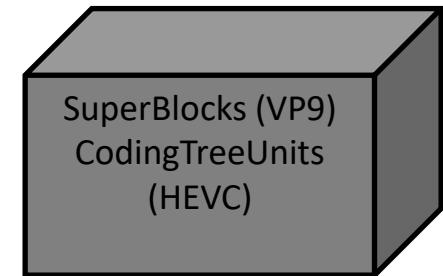
H.264 Vs MP4/2



HEVC/VP9?



Superblocks (VP9) Coding Units (HEVC)

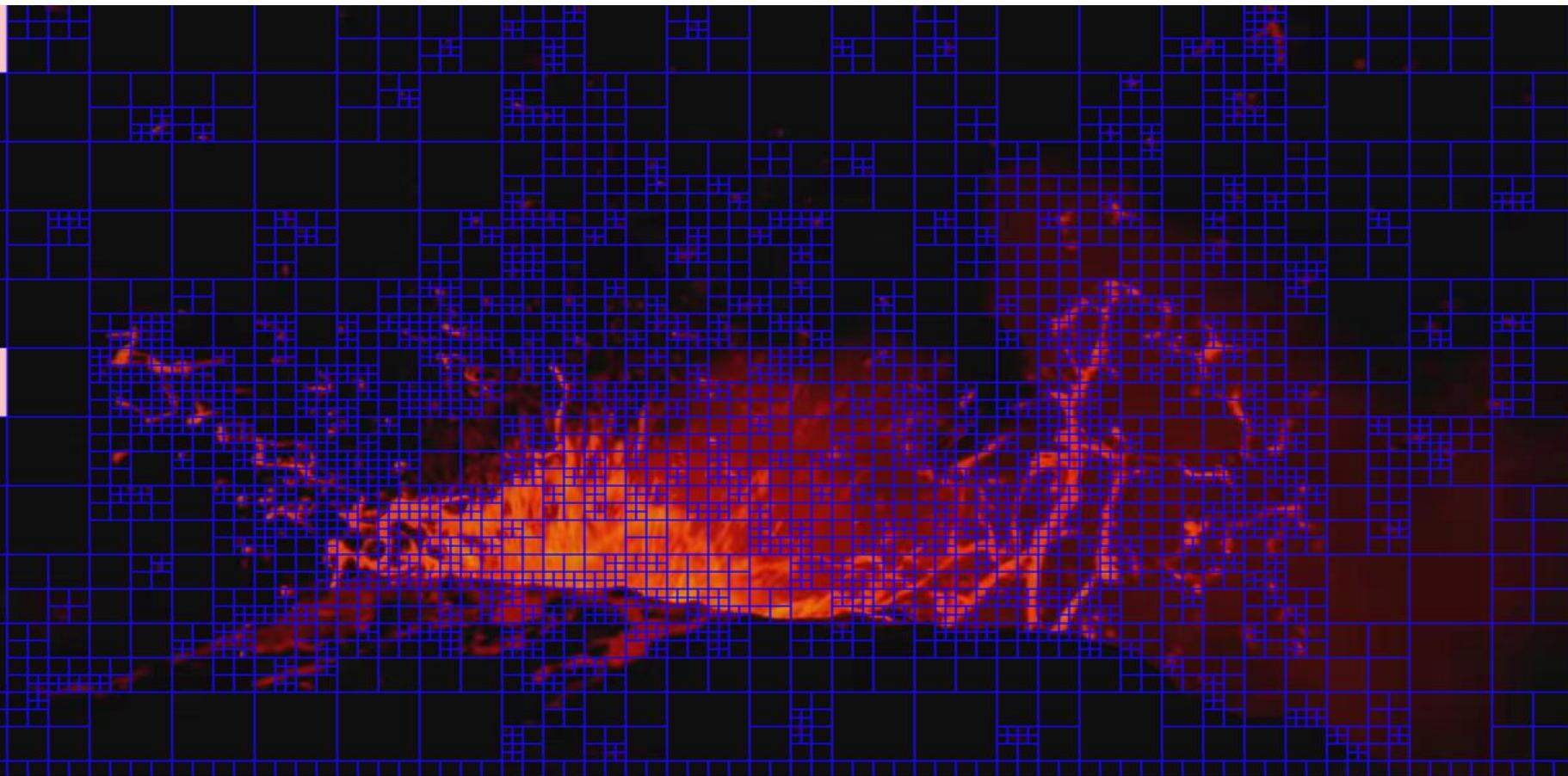


720p HEVC (H.265) – Intra Frame 0 103kbits, Intra Coding Units

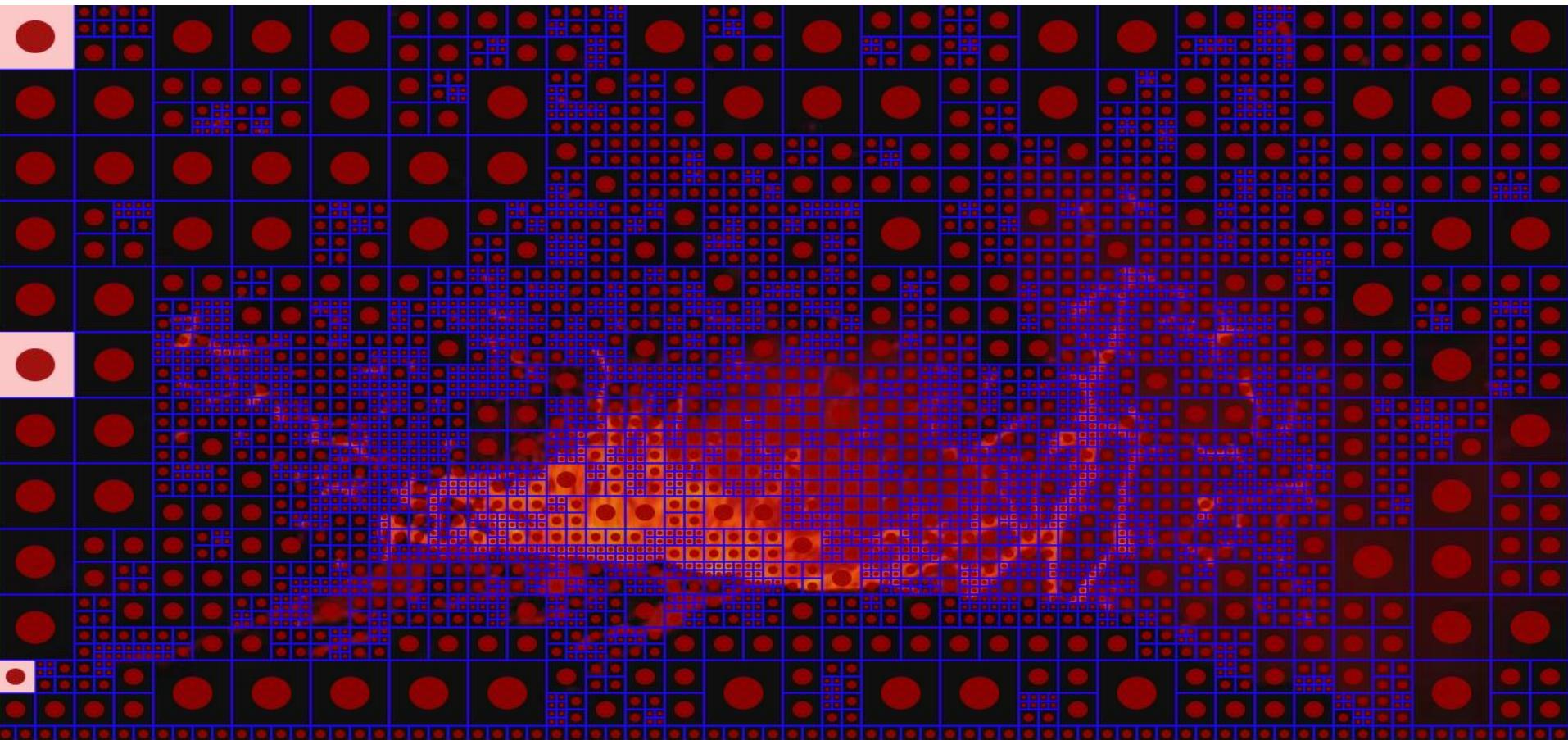


IDR (Instantaneous Decoding Refresh) Picture

720p HEVC (H.265) – Intra Frame 0 Showing CU's



720p HEVC (H.265) – Intra Frame 0 Showing CU's Intra



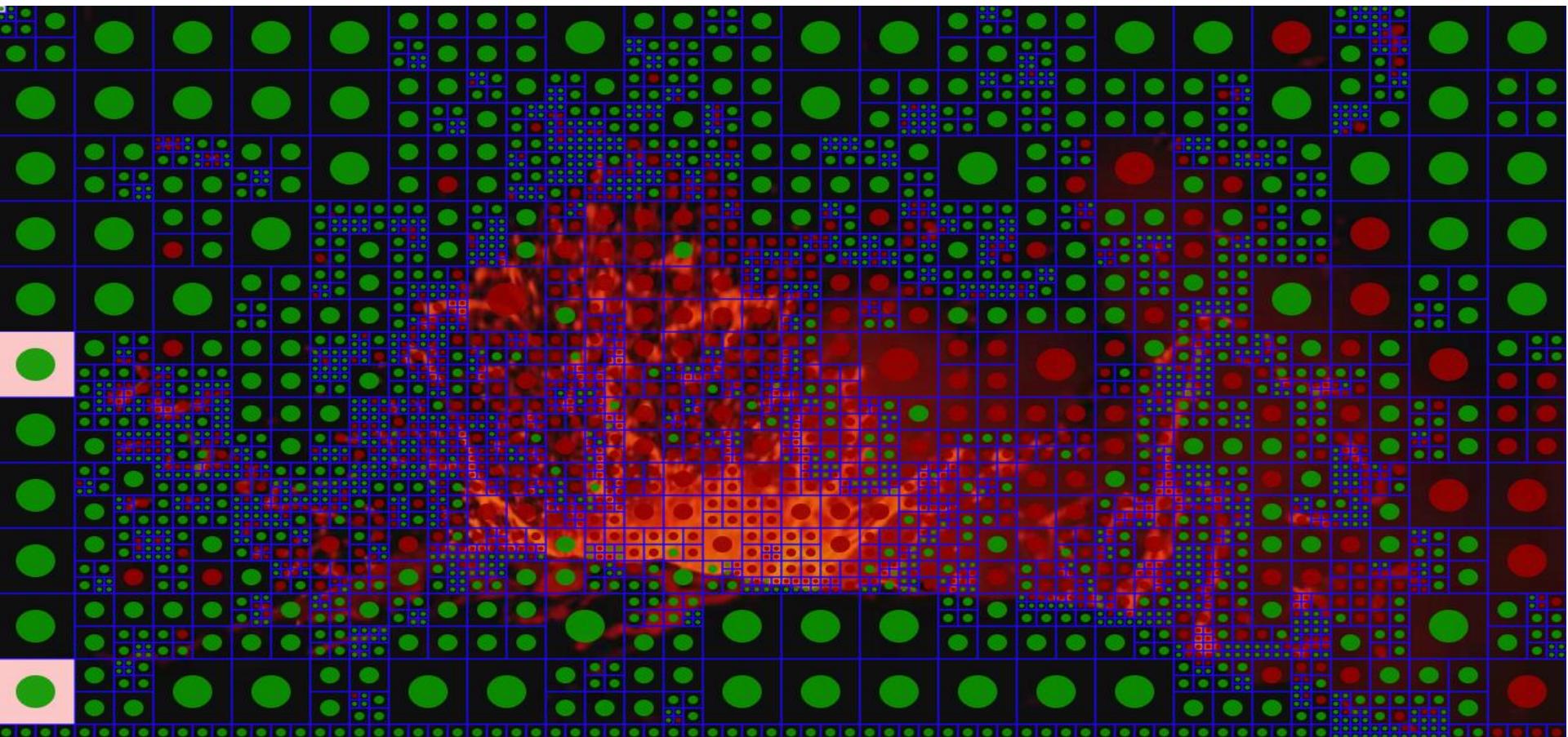
720p HEVC (H.265) – Frame 0 I-Frame



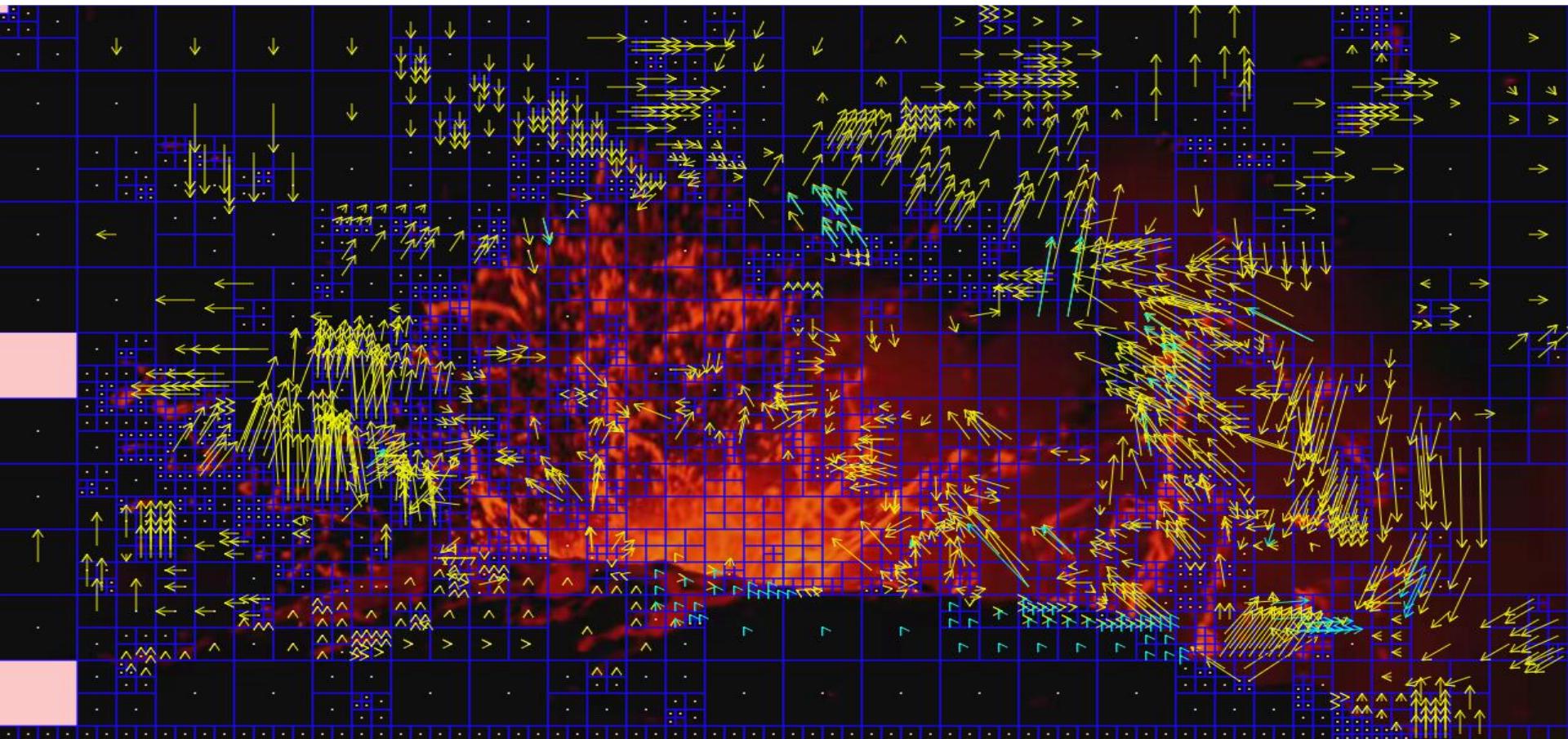
720p HEVC (H.265) – Frame 8 B-Frame 94.5 kbits



720p HEVC (H.265) – Frame 8 B-Frame, CUs and Type I/P



720p HEVC (H.265) – Frame 8 B-Frame Motion



720p HEVC (H.265) – Frame 0 I-Frame



720p HEVC (H.265) – Frame 8 Predicted B-Frame

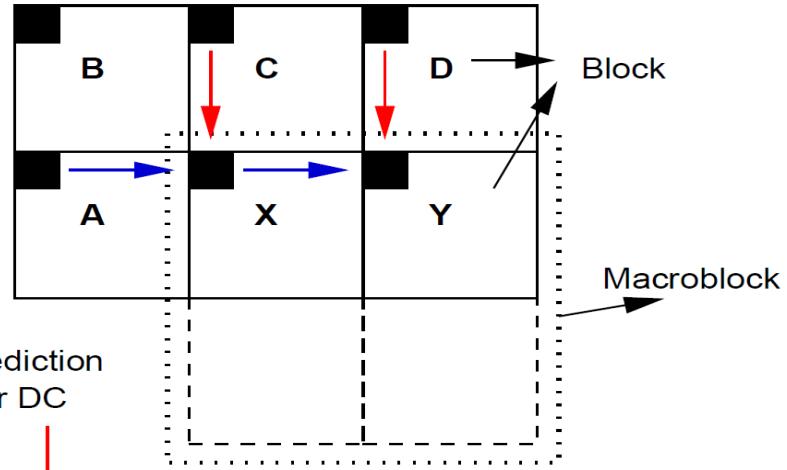
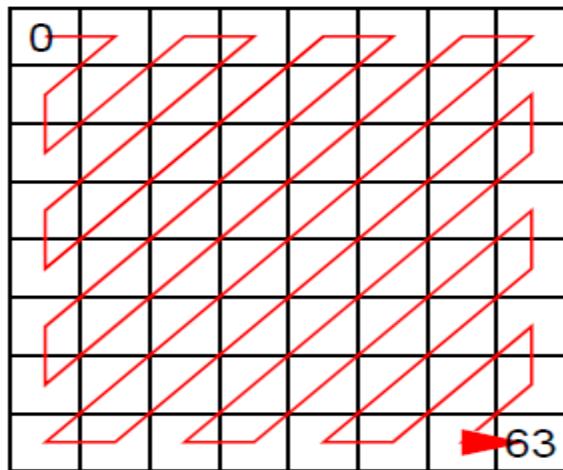


720p HEVC (H.265) – Frame 8 Final B-Frame



Prediction
Modes
Intra/Inter

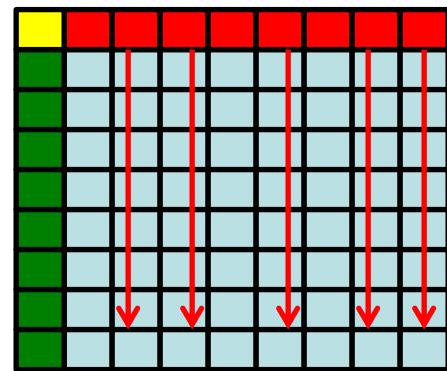
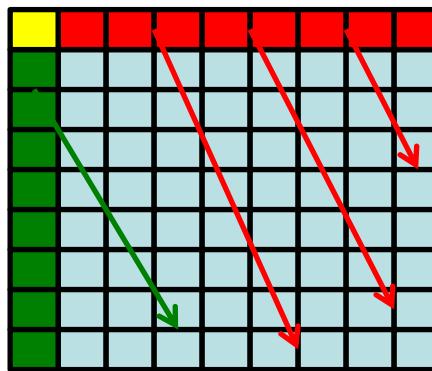
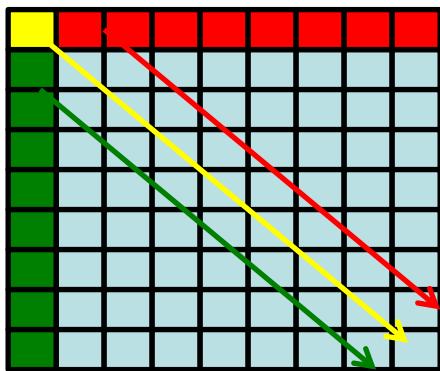
Intra Prediction Modes



DC Coefficient encoded differentially like JPEG
MPEG2 only allows prediction from left block,
Rest of coeffs encoded using run,length huffman codes (JPEG, MPEG2,4)

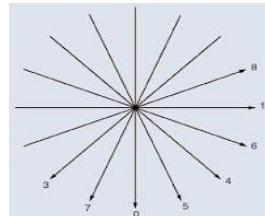
MPEG2 allows prediction spatially as well as temporally
H.264 also CABAC or CAVLC for difference between prediction and the observed coefficients

H.264 generates intra-block predictions using pixelwise copies

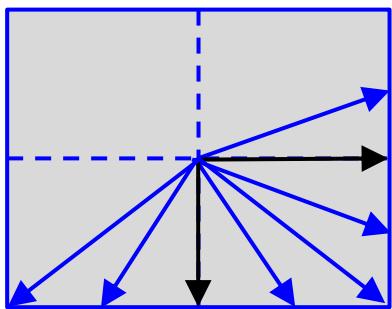


VP9 Uses Hybrid DCT/ADST for Intra Modes not DCT
Uses DCT for INTER Modes

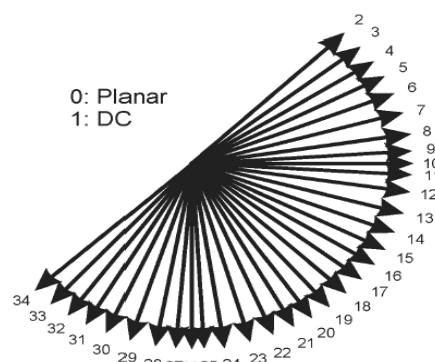
VP9/HEVC pushes this further (accounting for 10% over H.264)



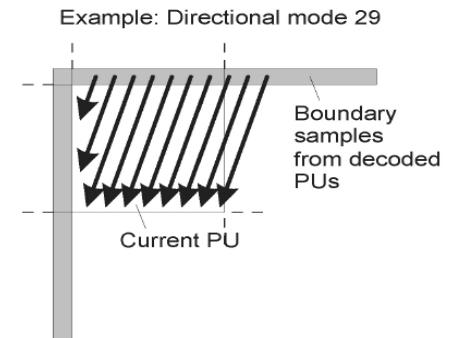
DC + 8 Directions
H.264



VP9 8 directions, along
with DC_PRED and
TM_PRED modes

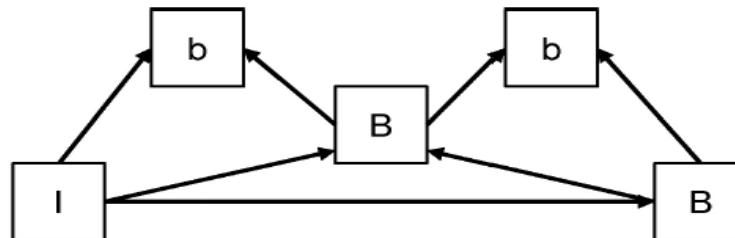


HEVC : DC + Planar + 33 Directions



Inter Prediction

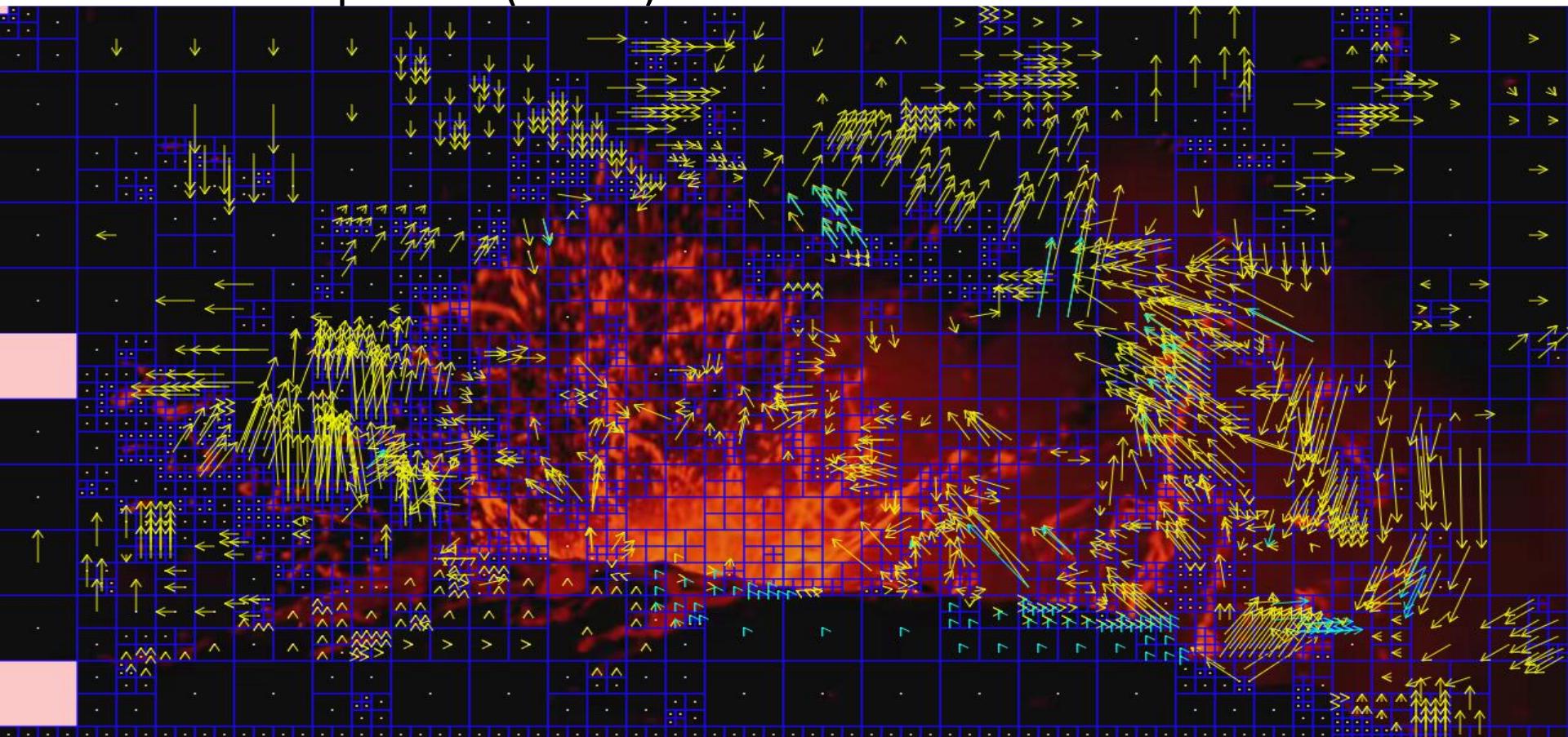
- VP9 allows coding a frame with a max of 3 reference frames, that are chosen per frame from a pool of 8
 - Every coded frame replaces one of the frame buffers as specified in frame header.
 - Certain frames can be designated *invisible* (Altref)



HEVC

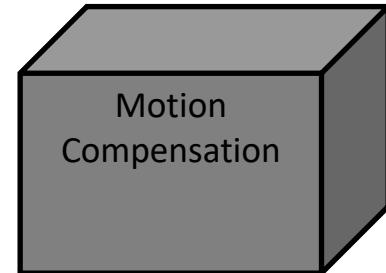
POC	0	1	2	3	4	Picture Order Count
Decoding order	1	4	3	5	2	
RPS	-	[0,2]	[0,4]	[2,4]	[0]	Reference Picture Set

720p HEVC (H.265) – Frame 8 B-Frame Motion



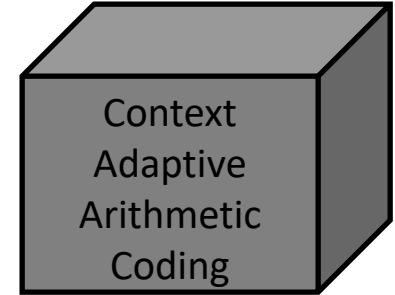
Trend is to do away with P/B frame distinction
allow prediction from one or more reference pictures on a CU basis

VP9 and HEVC Motion Compensated Interpolation



- Fractional motion compensation critical for video coding performance
- VP9 supports $\frac{1}{8}$ pel motion (1/16 in U and V)
- Frame level flag indicates whether $\frac{1}{8}$ is to be used
- Companded motion - use $\frac{1}{8}$ pel only for small motion as indicated by reference MV magnitude
- Use 3 different 8-tap filters + bilinear (regular/sharp/smooth)
- HEVC $\frac{1}{4}$ pel accuracy
 - Use 8tap and 7tap filters to interpolate picture directly
 - H.264 used two-step interpolation

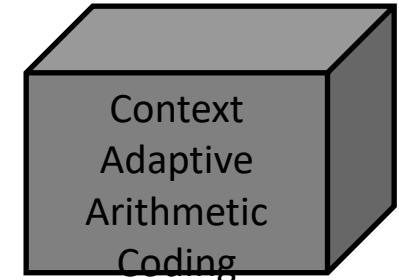
Context Adaptive Binary Arithmetic Coding



- VP9 Updates per frame only
- HEVC updates per block
- Uses a temporal smoothing of the symbol p.d.f's combined with simple p.d.f. models
- No temporal smoothing

Gain of 2-5% over CAVLC

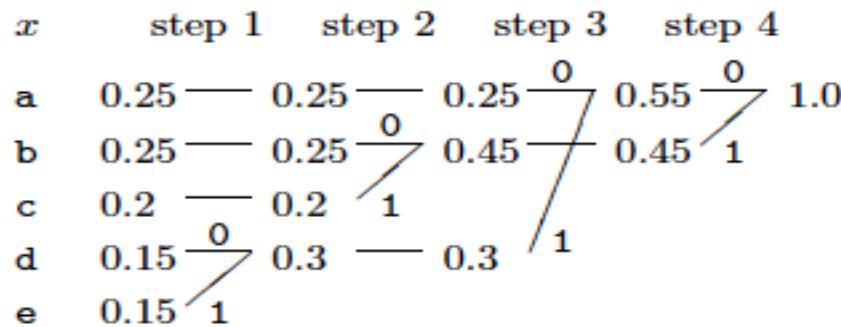
Context Adaptive Binary Arithmetic Coding



- Given the data to be coded a module is needed to assign bits to each datum for transmission.
- Up till 1998 the common thing to was Huffman Coding.
- Since 1999 the world switched to Arithmetic Coding thanks to a series of papers by Radford Neal et al (since 1987)
- Arithmetic coding achieves the Shannon coding limit, is very efficient and separates the process of coding from the process of p.d.f. measurement.
- All modern media compression uses some form of Arithmetic Coding.
H.264/HEVC/VP9 use “CABAC”

Gain of 2-5% over CAVLC

Huffman Coding Example



a_i	p_i	$h(p_i)$	l_i	$c(a_i)$
a	0.25	2.0	2	00
b	0.25	2.0	2	10
c	0.2	2.3	2	11
d	0.15	2.7	3	010
e	0.15	2.7	3	011

{ a, b, c, d, e }
{ 0.25, 0.25, 0.2, 0.15, 0.15 }

- Incurs an extra 0 or 1 bit per symbol
- Does not adapt to changing symbol p.d.f
- Typical patch up is to group symbols into blocks and code those

DC Coeff coding in JPEG, MPEG2/4

DC Coef Difference	Size	Typical Huffman codes for Size	Additional Bits (in binary)
0	0	00	—
-1, 1	1	010	0, 1
-3, -2, 2, 3	2	011	00, 01, 10, 11
-7, ⋯, -4, 4, ⋯, 7	3	100	000, ⋯, 011, 100, ⋯, 111
-15, ⋯, -8, 8, ⋯, 15	4	101	0000, ⋯, 0111, 1000, ⋯, 1111
⋮	⋮	⋮	
-1023, ⋯, -512, 512, ⋯, 1023	10	1111 1110	00 0000 0000, ⋯, 11 1111 1111
-2047, ⋯, -1024, 1024, ⋯, 2047	11	1 1111 1110	000 0000 0000, ⋯, 111 1111 1111

Run/length huffman coding for AC Coeffs

As an example, let us code the following 8×8 block:

-13	-3	2	0	0	0	1	0
6	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
-1	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0

Code Run of zeros together with the SIZE of the non-zero coefficient at the end.
Max length of run is 15.
ZRL for any run more than 15 zeros, so ZRL = 15 zeros followed by a 0

Converting this to (DC Size) or (Run,Size) and values for the Additional Bits gives:

(4)	-13	(0, 2)	-3	(0, 3)	6	(2, 2)	2	(3, 1)	-1	(ZRL)	(1, 1)	1	(EOB)
101	0010	01	00	100	110	11111001	10	111010	0	11111111001	1100	1	1010

CABAC in H.264 : Responsible for 9-14% gain over run/length with fixed tables (baseline H.264)

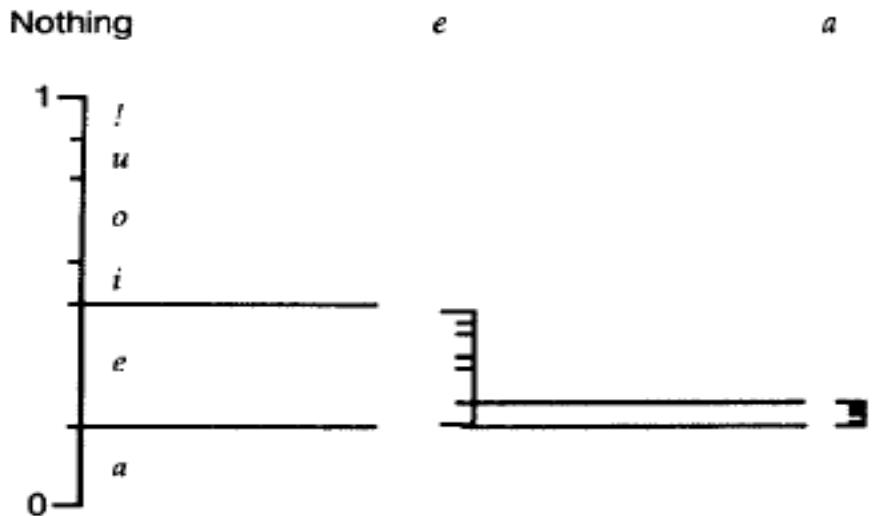
Context Adaptive Binary Arithmetic Coding / Variable Length Coding

Basic idea is to use different VLC tables that depend on a categorization of the nature of a block. This is done through some analysis of a significance map of a block and using the state of the blocks to the top and left of the current one.

Context Based Adaptive Binary Arithmetic Coding in the H.264/AVC Video Compression Standard, Detlev Marpe, Heiko Schwarz, and Thomas Wiegand, IEEE TRANSACTIONS ON CIRCUITS AND SYSTEMS FOR VIDEO TECHNOLOGY, VOL. 13, NO. 7, JULY 2003

Arithmetic Coding (A Fast Introduction)

Symbol	Probability	Range
a	.2	[0, 0.2)
e	.3	[0.2, 0.5)
i	.1	[0.5, 0.6)
o	.2	[0.6, 0.8)
u	.1	[0.8, 0.9)
!	EndOfBlock	[0.9, 1.0)

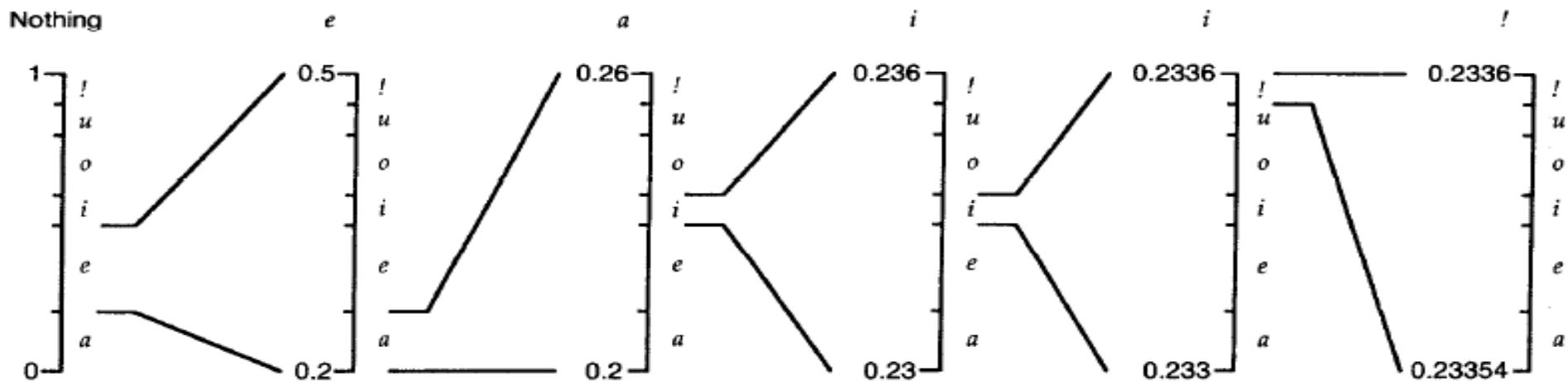


Encode e, a, i, i, !

Arithmetic Coding (A Fast Introduction)

Arithmetic Coding for Data Compression, Witten,
Radford, Neal, Cleary, *Communications of the ACM*,
vol. 30, no. 6, pp. 520-540, June 1987.

Encode e, a, i, i, !



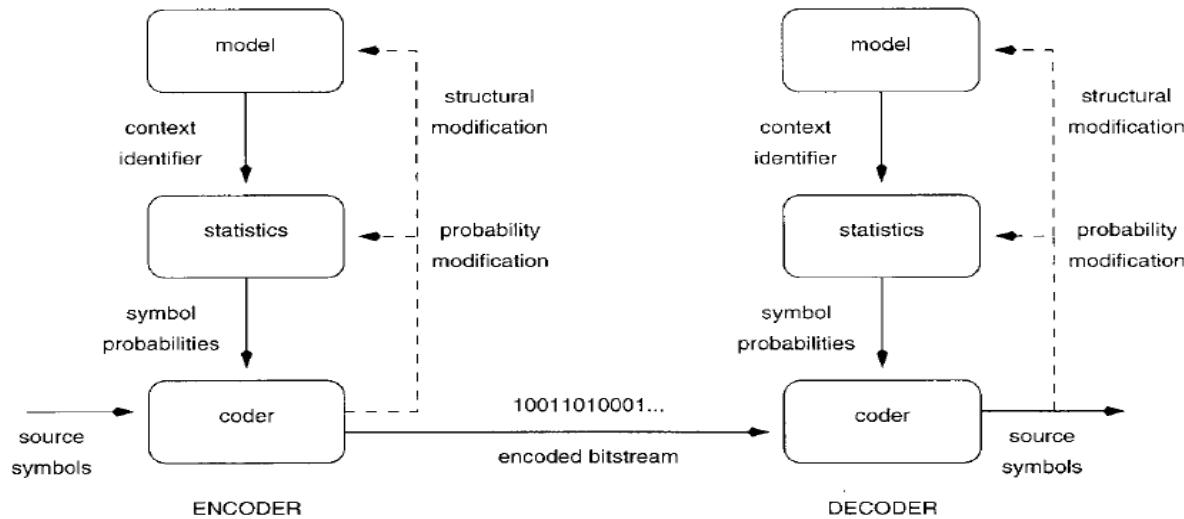
Decoder is a matter of recursive interval “spotting”

Gets arbitrarily close to the Shannon Limit for long streams of bits

Can change p.d.f. as you collect more “context”

More complicated than Huffman but recent work uses integer arithmetic instead

Arithmetic Coding: Separating Coding from Modelling

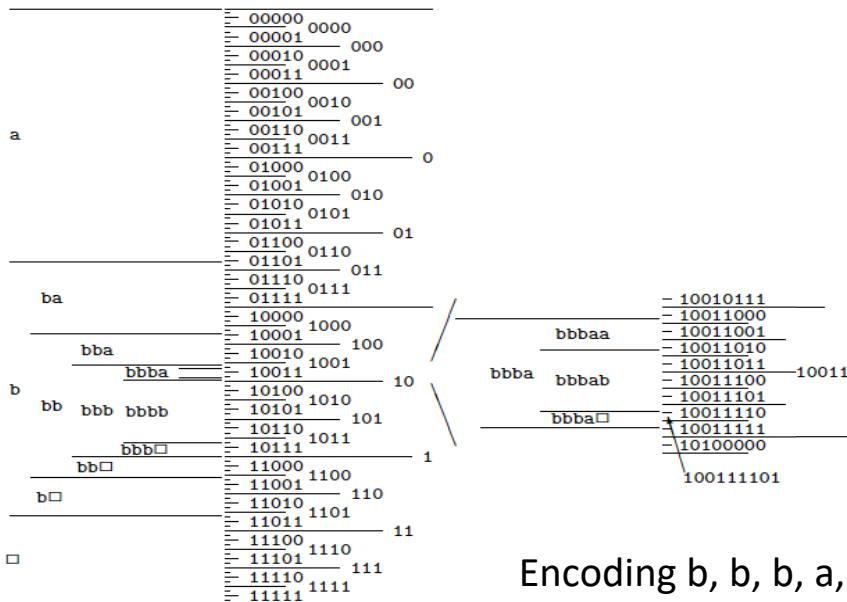


Arithmetic Coding Revisited, Moffat, Neal and Witten, *ACM Transactions on Information Systems*, Vol. 16, No. 3, July 1998, Pages 256–294.

This paper proposed practical schemes and led to CABAC used today

Arithmetic Coding: Using integer representation

Context (sequence thus far)	Probability of next symbol		
	$P(a) = 0.425$	$P(b) = 0.425$	$P(\square) = 0.15$
b	$P(a b) = 0.28$	$P(b b) = 0.57$	$P(\square b) = 0.15$
bb	$P(a bb) = 0.21$	$P(b bb) = 0.64$	$P(\square bb) = 0.15$
bbb	$P(a bbb) = 0.17$	$P(b bbb) = 0.68$	$P(\square bbb) = 0.15$
bbba	$P(a bbba) = 0.28$	$P(b bbba) = 0.57$	$P(\square bbba) = 0.15$

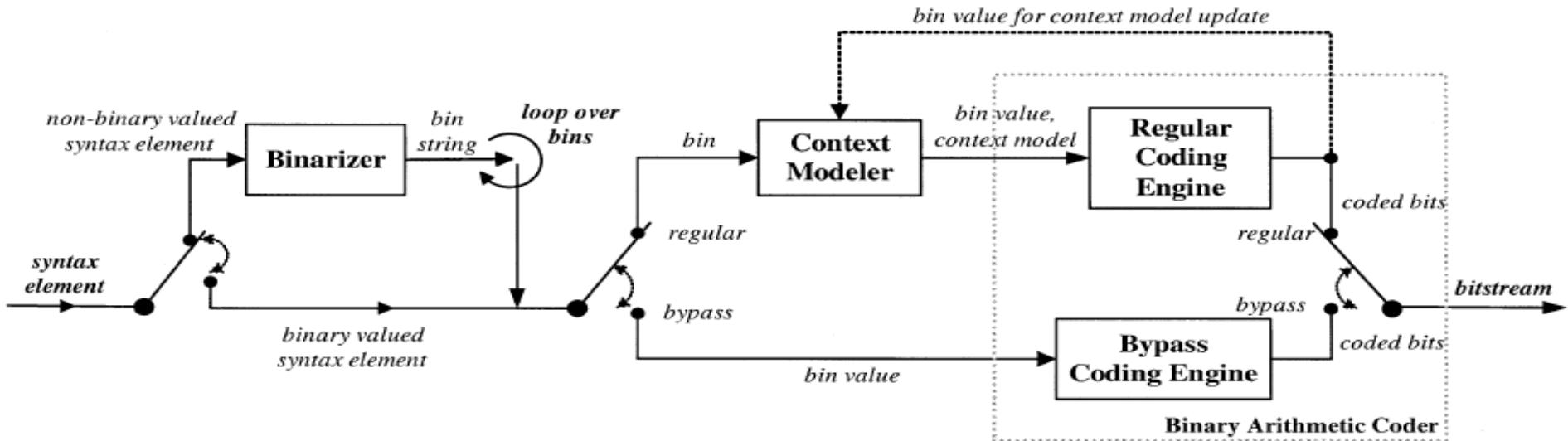


Use binary intervals
Ship bits when stable

See pages 112-114 of
Information Theory by MacKay

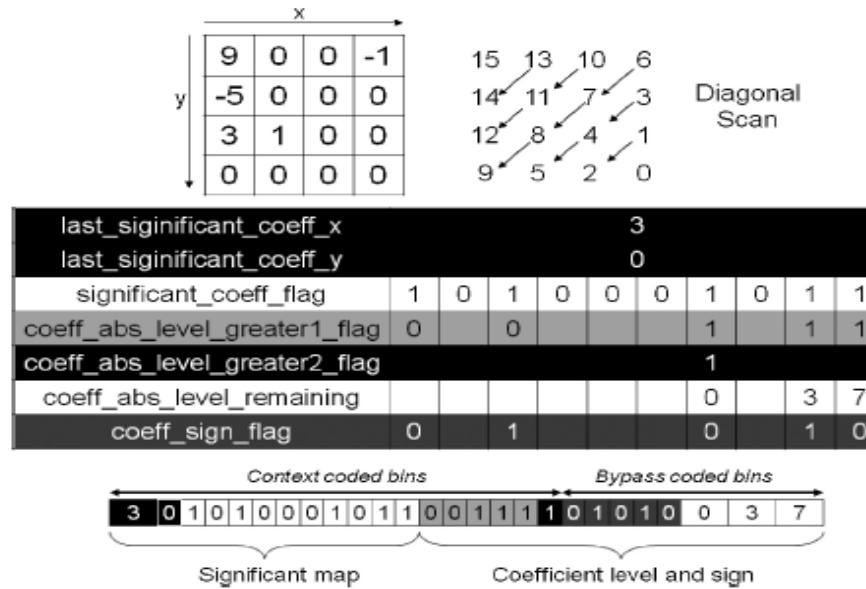
Encoding b, b, b, a, EoB

CABAC in H.264 and HEVC



Context-Based Adaptive Binary Arithmetic Coding in the H.264/AVC Video Compression Standard, Detlev Marpe, Heiko Schwarz, and Thomas Wiegand, *IEEE Trans Vid Ccts and Sys*, Vol 13, No 7, July 2003, pp 620-636

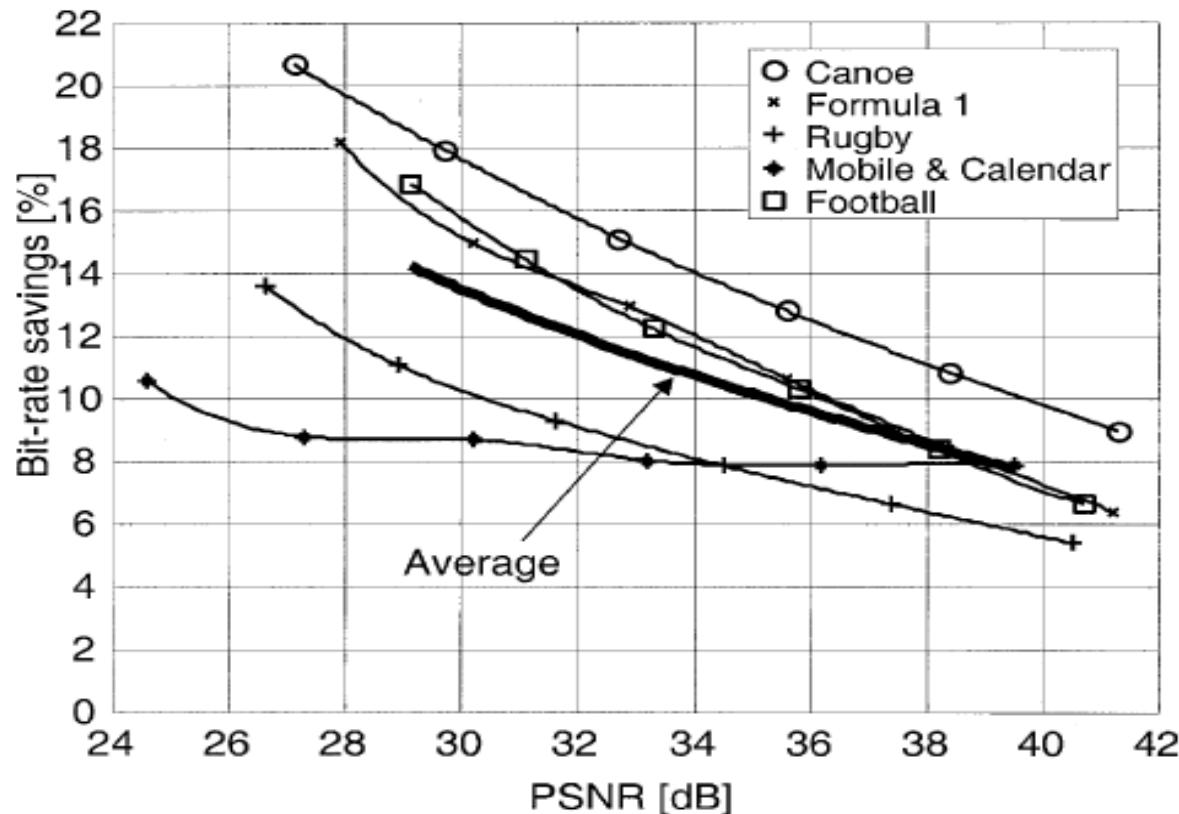
CABAC for DCT in H.264 and HEVC



Key Challenges: High throughput, Low complexity and Low Memory (esp for hardware)

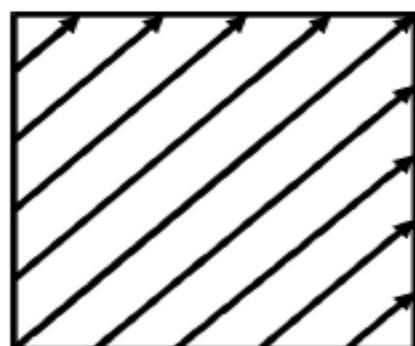
High Throughput CABAC Entropy Coding in HEVC, Vivienne Sze and Madhukar Budagavi, *IEEE Trans Vid Ccts and Sys*, Vol 22, No 12, Dec 2012, pp 1778-1791

CABAC in H.264 Vs CAVLC H.264 Baseline

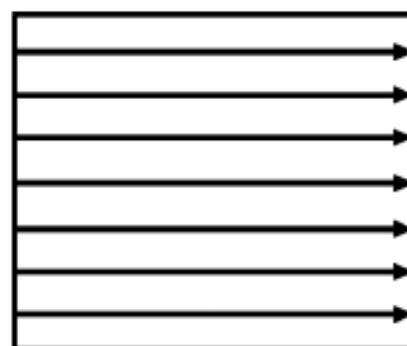


3 Scan Patterns in HEVC

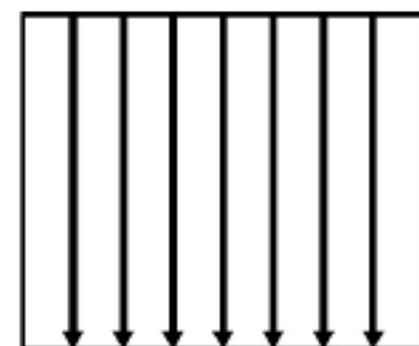
HEVC and VP9 not defined for Interlaced video



(a)



(b)



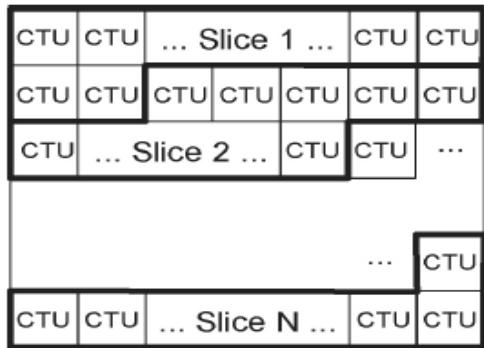
(c)

VP9 CABAC

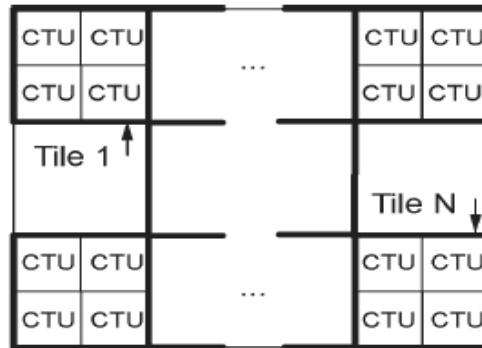
- Very similar to CABAC in HEVC in spirit
- Different models (some parametric)
- Different binary symbols (different coding tree)
- Update models only every frame instead of every symbol
- 2-3% Improvement over CAVLC (Huffman++)
- Compromises made for fast operation in hardware

Sequencing (HEVC)

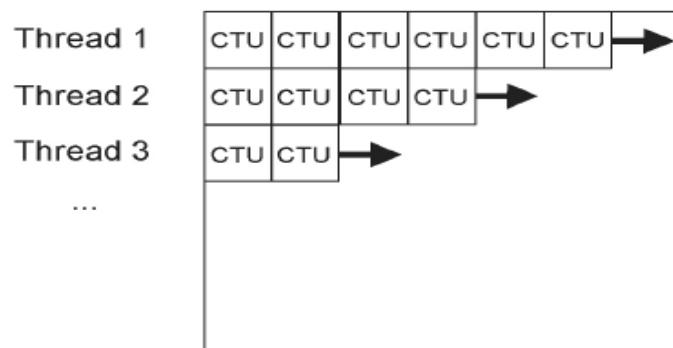
Tiling/Slicing
Sequencing



(a)



(b)



(c)

A note on synchronisation

The codes are all Variable Length Codes

This is why synchronisation is a problem.

So if you forget where you are in the bitstream somehow, you will start to confuse one code with another.

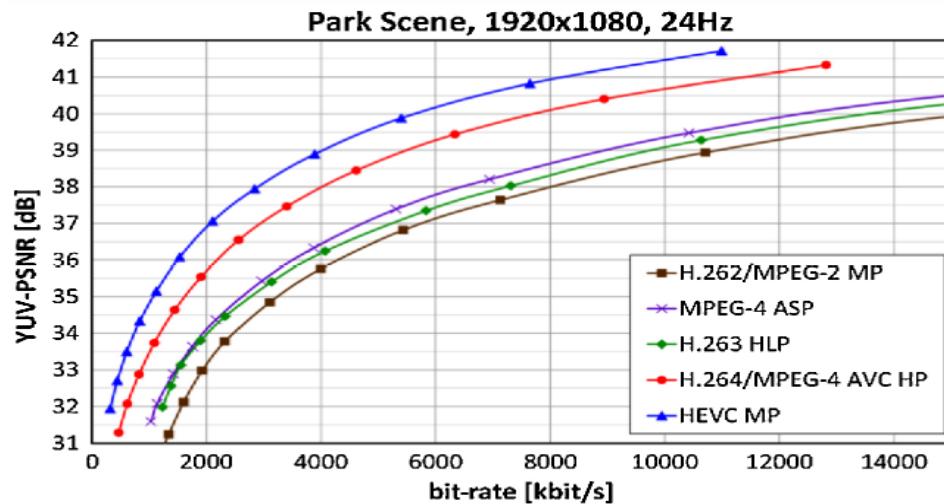
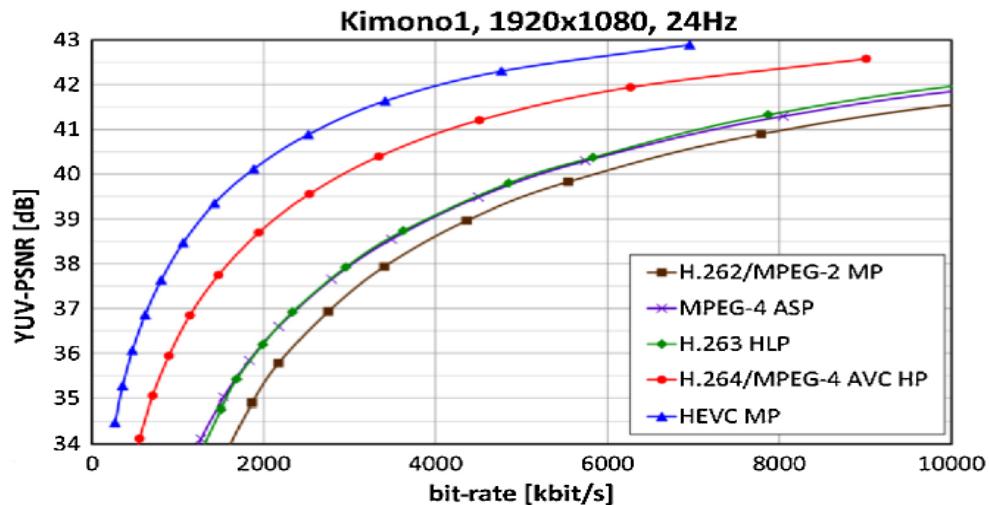
If you detect a problem, you can skip to the next unique code you can recognise. This can be a special code or just a clever decoder spotting the next macroblock header,

MPEG4 uses the Resynchronisation marker :

0000 0000 0000 0000 1

MPEG2 uses the slice header. H.264 uses video packet header.
VP9 and HEVC use SLICES for resync

HEVC Performance



More Reading

Overview of the High Efficiency Video Coding (HEVC) Standard, Gary J. Sullivan, Jens-Rainer Ohm, Woo-Jin Han and Thomas Wiegand, *IEEE Trans Vid CCts and Sys*, Vol 22, No 12, Dec 2012, pp 1649-1668

Information Theory, Inference and Learning Algorithms, David MacKay, CuP 2003, Online version at <http://www.inference.phy.cam.ac.uk/mackay/itila/>

Excellent video lectures by Prof. MacKay
http://www.inference.phy.cam.ac.uk/itprnn_lectures/ [Lecture 5 of most relevance to CABAC]

Google's WEBM project <http://www.webmproject.org/>

VP9 : <http://www.webmproject.org/vp9/>

VP9 Vs H.264

https://x20web.corp.google.com/~jimbankoski/vp9/same_bitrate.html

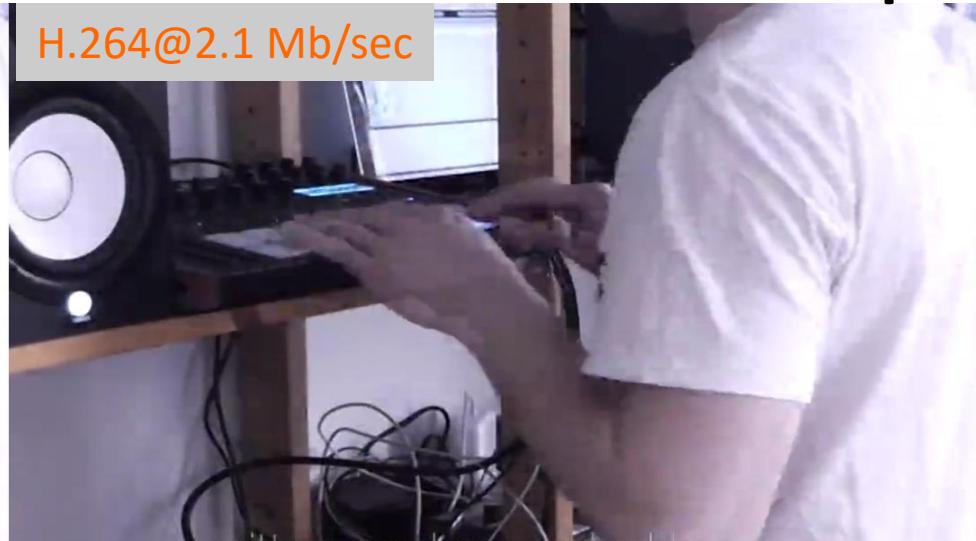
- Have to use a browser to play this since Chrome is the only VP9 player easily usable in a presentation like this

720p



VP9 Vs H.264

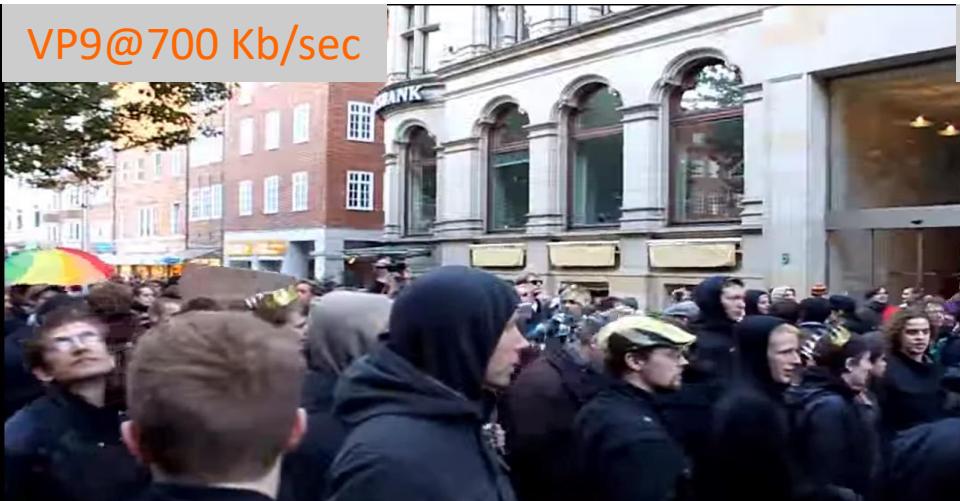
720p



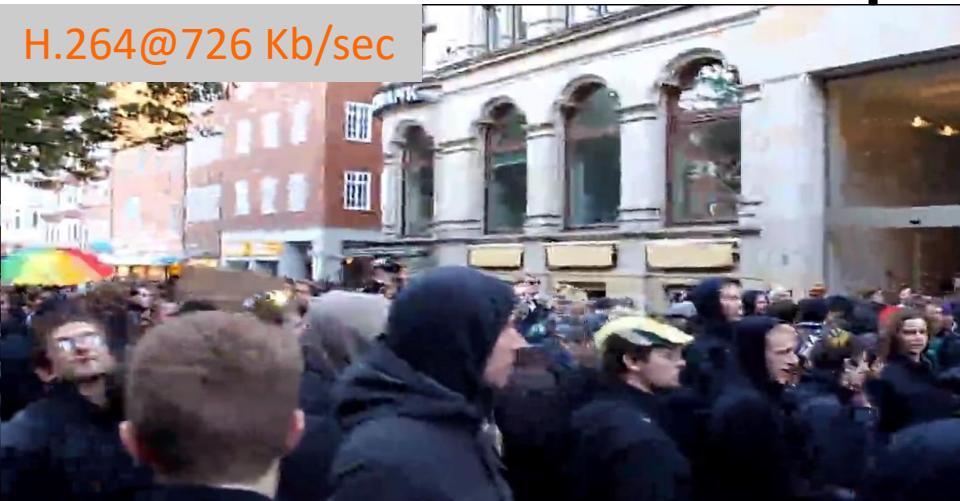
VP9 Vs H.264

720p

VP9@700 Kb/sec



H.264@726 Kb/sec



Final Comments

- Video is breaking the internet
- Need to keep improving compression, keep increasing bandwidth, keep reducing cost
- HEVC and VP9 are the new wave of compression algorithms
- Based on new tools : larger blocks, quadtree, arithmetic coding
 - VP9 already supported in Chrome. HEVC at first had better hardware traction but VP9 has caught up.
- NOTE: Standards do NOT specify coding methods only the BITSTREAM SYNTAX. Standards docs are pretty tricksy to read (try it), you are trying to describe program code in words. That is why Google's Chrome Media doesn't write a lot of them.
- Next : Trading off bandwidth/compression/cost