The true reasons for a full frame camera

– White Paper –

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Abstract

Full frame photo cameras are a recurring theme in considerations about the best system camera for a given task. By full frame, we mean a camera with a full 24 mm x 36 mm sized capturing device.

This paper tries to give general criteria to decide when a full frame camera would be the best option. As it turns out, there are a number of ambitious situations where full frame is indeed the most cost-efficient or only option. Whereas in other situations, a smaller sensor camera (e.g. a camera with a 1.5x-cropped frame of 16 mm x 24 mm APSC size) can be more cost efficient. This paper tries to quantify the corresponding regimes where one or the other format would be more appropriate.

This text absolutely requires a careful read of the foundation of every camera comparison, summarized here:

- www.falklumo.com/lumolabs/articles/equivalence [camera equivalence]

It is not possible to read this paper without a good understanding of the principles of camera equivalence. Please, follow the above link and come back here when done. Thanks.

1. Factors of consideration

For the sake of simplicity, we will mostly confine our reasoning to two formats: APS-C and 35mm full frame. Moreover, I'll often replace the crop factor of 1.5 by √2 which leads to a difference of one stop in many comparisons.

1.1. Form factors and price

Fig. 1 Comparison of form factors between a ***hypothetical*** compact full frame body (D800c) and an existing full frame body (Nikon D800, right). This D800c is 8 mm higher and 10 mm wider than a Pentax K-5, i.e., it is 141 x 105 mm^2. Which is somewhere between a Nikon D7000 (same height) and Canon 7D.

The forthcoming Nikon D600 will sit in between the D800 and D800c. The D600 is not as tall as the D800.

Let's start with the most commonplace arguments *against* a full frame camera: it is bulky, heavy, expensive as are its lenses.

Well, if you look at camera equivalence, you'll see it isn't true for lenses and equivalent full frame lenses tend to be cheaper actually. But how about the body?

Existing full frame bodies are large indeed. Larger than they need to be. In Fig. 1, I compare the full frame Nikon D800 with a hypothetical, more compact full frame D800c. The D800c is derived from the Pentax K-5 (APSC), *enlarging* its body by the extra dimensions of a 24x36mm sensor over a 16x24mm APSC sensor (or mirror) and replacing the mirror box and prism by a full frame one. Note the K-5 body has in-body image stabilization while Nikon has not, meaning that the D800c body could be made even smaller than in the above image. Moreover, there is no strong reason to enlarge the outer dimensions of an APSC camera with a full frame mirror box at all. Because the back of the mirror box is large enough to accommodate a larger sensor. And because the AF module (sitting in the camera bottom) is normally the same as found in APSC models. So, the above size comparison is conservative. Still, it shows that APSC-sized full frame cameras are more than feasible.

So, using the same level of integration as Pentax does in their APSC offerings, a D800 or Canon 5DmkIII body could be made substantially smaller and probably would hit most enthusiast photographers' sweet spot for size.

Nikon actually tries to do so with their forthcoming D600. It is an intermediate step between the D800 and what would be feasible.

There is another way to see how a full frame camera can be small: Imagine a hypothetical full frame Sony NEX-9: it would be a bit larger than a NEX-7. But not by much because the NEX-7 already has a mount of sufficient size (E mount) and processing power (24 mega pixels) on board. And it would still look tiny next to a D800 (body only).

So overall, body size or weight is not an à priori argument against full frame. However, there is still a market niche for smaller propositions. Many people though can live with a camera the size of a D800 just fine.

As far as pricing is concerned, I am convinced that prices will go down rapidly when people just stop buying APSC SLR cameras. What will happen, or is happening already. A D800 body at $ 3,000 may look like a great value proposition. But according to my own research, the most expensive component (the full frame sensor) is less than about $ 300 purchase price for the camera vendor. So, a full frame camera could run at about $ 500-$ 900 above an equally specified APSC camera which is closer to $ 1,500 to $ 2,500 rather than $ 3,000. Full frame SLR cameras will soon be sub $ 2,000 items and absolutely rule the enthusiast SLR market.

After I wrote the above sentence, rumors emerged that the forthcoming Nikon D600 will sell at $ 1,500. Sounds too aggressive for many, but I wouldn't rule it out based on my considerations.

Now taking into account that equivalent lenses for APSC easily cost $ 500 to $ 1,500 more per unit (cf. below), I'll say that price too isn't a valid argument against full frame anymore. Or soon won't be.

1.2. Lens options

The paper on camera equivalence explains how to properly compare cameras and their lenses: E.g., you compare a 200 mm F/2.8 lens for APSC with a full frame 300 mm F/4 lens; both are equivalent.

Using equivalent lenses, a camera with a bigger sensor has no immediate advantage. They are equivalent. Therefore, the question must be restated: Which lens options do exist when expressed in equivalent terms? Because an option which does not exist for one format puts it at an disadvantage.

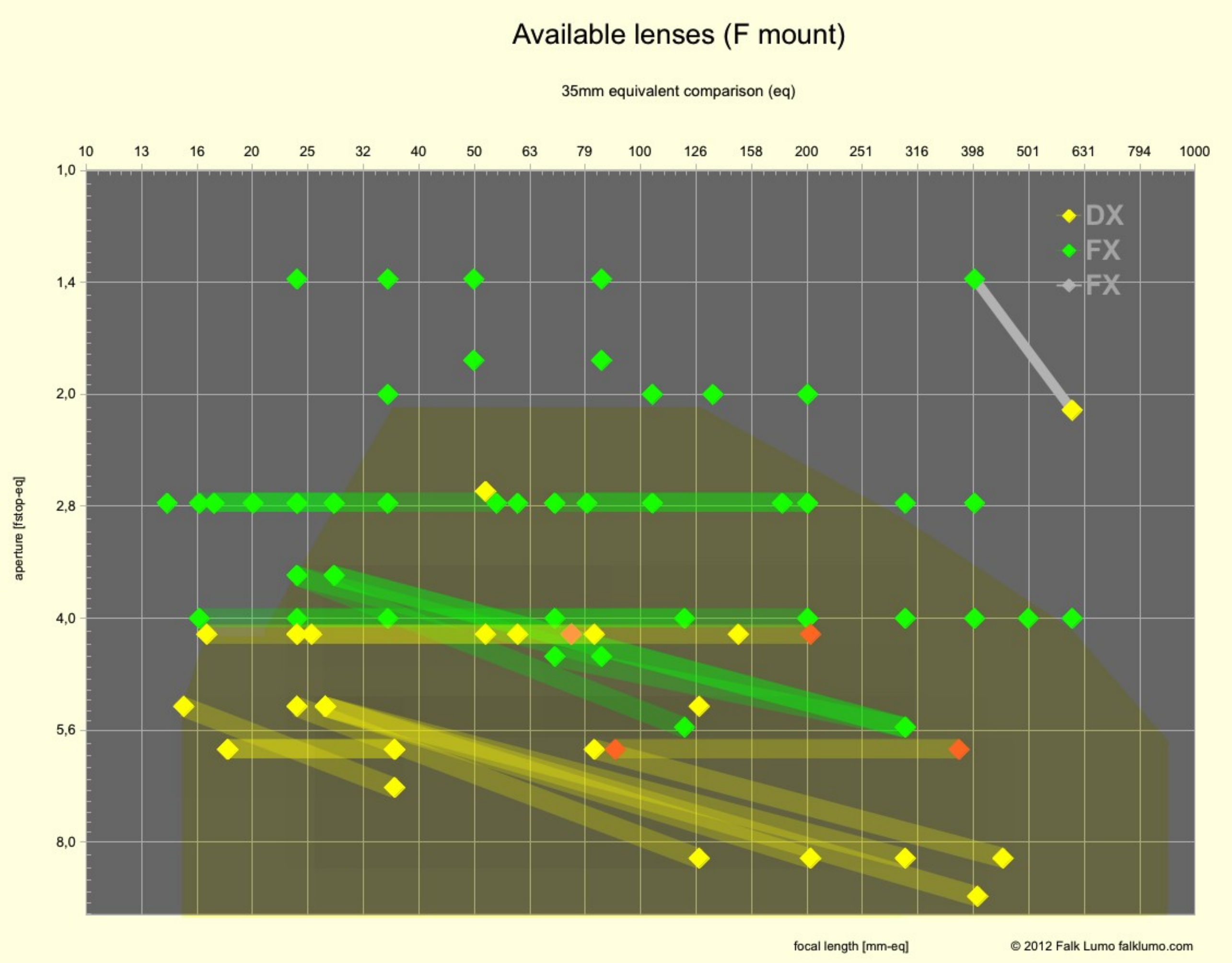

Fig. 2 Most available lenses for Nikon APSC cameras (DX) and Nikon full frame cameras (FX).

All focal lengths and *all* apertures are expressed in 35 mm equivalent terms. Zooms are marked by a line from wide to tele. The shift of verbatim DX to equivalent parameters is shown by the gray line in the upper right-hand corner.

Because APSC cameras can also use full frame lenses, each FX lens, when used on an APSC camera, doubles as DX lens. The combined area covered by DX and doubled FX lenses is shaded dark yellow.

As shown in Fig. 2, the combined area covered by APSC and full frame lenses used on APSC (the shaded dark yellow area) does not cover some options available for full frame.

These options are basically F/1.4 and F/1.8 lenses, F/2.8 wide angles from 14 mm to 25 mm and a F/2.8 tele at 400 mm.

On the other hand, full frame does not cover 800 mm F/5.6 equivalent lenses. However, this does not hold true for a type-2 equivalent full frame camera (like the D800 when compared to a D7000) which have the same pixel pitch and where a full frame camera doubles as crop camera. Even with type-1 equivalency, it does not hold true if you allow tele converters to be used.

Considering zooms, it is obvious that there are no equivalent F/2.8 zooms available for APSC. For some reason, APSC-only vendors never tried to fill the gap by offering APSC zooms with a nominal F/1.8 aperture. Pentax has highly regarded nominal 16-50/2.8, 50-135/2.8 and 60-250/4 lenses which I included in the plot above (orange points) because they are a more serious attempt to make APSC competitive.

(There are also highly regarded nominal 14-35/2 and 35-100/2 Zuiko lenses for FourThirds (crop 2); but because of the larger crop, they are only equivalent F/4 zooms either; moreover, they are very expensive ($ 2,000 each) underlining the claim that increasing the crop factor tends to make equivalent lenses more expensive).

So, to summarize, in comparison to APSC, full frame adds lens options for:

- F/2.8 ultra wide angle and ultra tele (compared to F/4 equivalent)
- F/1.4 primes (compared to F/2 equivalent)
- F/2.8 quality zooms (compared to F/4 equivalent)
- F/~4 consumer zooms (compared to F/~5.6 equivalent)

I.e., overall there is a one stop advantage in available lens options for full frame. Note however, that using these options will make the full frame system more expensive. So, this advantage is optional and comes at a certain price.

Many people prefer to use affordable “equivalent” lenses (like a full frame 70-200mm F/4 or 24-120mm F/4 zoom) and just add a “non-equivalent” fast prime like a 50mm F/1.4 to their set-up.

> *Here, by “equivalent” and “non-equivalent”, I mean full frame lenses where equivalent APSC lenses exist or don't exist, resp.*

This strategy makes perfect sense. So far, a full frame camera isn't better as such. It only offers additional freedom.

Nevertheless, I should emphasize one advantage of APSC: There are “APSC-style” lenses which are lighter than traditional full frame offerings because the vendors never cared. By APSC-style lenses, I mean lenses like an APSC kit lens (18-55mm F/3.5-5.6) which are 27-83mm F/5.3-8.4 equivalent. Or generally, lenses between F/5.6 and F/8.0 aperture in equivalent terms. Such lenses are slow. But they are light, can be made tack-sharp and esp. for longer focal lengths, could make a big difference in affordability. The current lack of APSC-style full frame lenses has no technical reason. Moreover, adding a tele converter converts some of such lenses into full frame APSC style.

Nikon already seems to anticipate the need for APSC-style full frame lenses, e.g., they just filed a patent for a 24-70mm F/3.5-4.5 full frame lens (D600 kit lens). I foresee more smaller and relatively lightweight full frame lenses in the future, such like a 40mm F/2.8 pancake, 24-200mm F/5.0-8.0, 500mm F/5.6 or a 120-400mm F/4.5-5.6 which already exists from Sigma (although not tack-sharp ;)).

1.3. Image quality

Between ideal type-1 equivalent cameras, there is no difference in image quality. So, there is no difference between an ideal APSC and full frame camera. Period.

But non-equivalent lenses exist (cf. above), i.e., full frame lenses where no equivalent APSC counterpart exists. And if used at an appropriate aperture, the difference will be obvious.

Only then will be there such a thing as a more shallow depth of field. With equivalent lenses, there won't be.

But that's all covered above. We'll look now at non-ideal equivalent cameras, i.e. using equivalent lenses with real-world, non ideal performance.

1.3.1. Sensor resolution

Sensor resolution is the same for type-1 equivalent cameras and it is larger by $crop^{-2}$ for type-2 equivalent cameras. Interestingly, the market seems to converge to a situation where sensor resolution scales a lot like $crop^{-1}$.

E.g., the difference between a Nikon D7000 and a D4 is type-1 equivalent (both are 16 MP: $\sim crop^{0}$), between a D7000 and D800 is type-2 equivalent ($\sim crop^{2}$). And between a Sony NEX7 and D800, it is in between ($\sim crop$). Moreover, I expect APSC cameras to have 36 MP before the next iteration of full frame sensors (we must not forget the Nokia 808 mobile phone already features 41 MP...).

Personally, I believe that resolution with conventional CMOS pixel technology will settle around $crop^{-1}\ x$ 100 MP. Which is a figure between 12 MP for cheap mobile phones, to 25 MP for FourThirds, 65 MP for APSC, 100 MP for full frame to 160 MP for uncropped medium format.

But of course, this is an arbitrary scaling law. I think, a 2.9 μm pixel for 100 MP with a full frame camera has a good size. However, the pixel quality of a 12 MP mobile phone (1.1 μm) will be far inferior to that of a 160 MP uncropped medium format camera (3.7 μm) in practice. With the pixel size of current mobile phone cameras, medium format cameras could be Gigapixel cameras.

In theory, pixels < 1 μm are doable if diffraction-limited (sharp) <F/1.2 lenses can be made. In practice though, full frame cameras have a resolution advantage over APSC cameras.

Note however, that sensor resolution does not directly contribute to image quality. Only few output media like large fine art printers support resolutions in excess of 10 MP. But it adds to the flexibility of a system.

And it removes a source of blur from the image forming chain: rasterization and possible low pass filtering have a modular transfer function (MTF) which has a negative impact at lower spatial frequencies too. An image downsampled from a higher resolution to a destination resolution will look sharper than one captured at that resolution, everything else being equal.

Overall, a larger sensor will have a positive impact on image quality if we don't exactly consider type-1 equivalent cameras.

1.3.2. Lens blur

As noted [camera equivalence], the lens resolving power expressed in effective megapixels *MP* depends on the sensor size s:

$$MP_{lens} = \sim \mathbf{s}^{p} \text{ with } \approx 1 < p < \approx 3$$

where the larger value for p is achieved in the center and the lower one in the corners. There is a strong dependence on actual lens construction and if lenses are constructed expensive enough, p might be smaller by 1. Note that the above formula is only valid for equivalent lenses which aren't diffraction limited. As soon as diffraction limited, equivalent lenses perform the same.

So, the above says the following:

Equivalent full frame lenses reach their diffraction-limited performance quicker than their APSC counterparts, esp. in the center. But because APSC lenses may actually perform diffraction-limited (or outresolving the sensor) in the center too, the difference in corner performance may be more noticeable.

It is a myth that APSC cameras crop the "sweet spot" from the center of full frame lenses. Such myths can arise when comparing non-equivalent cameras … (cf. [camera equivalence §4.2.2] for further detail).

Overall, equivalent full frame lenses deliver better image quality. Or at a given image quality, they are cheaper (like in consumer grade full frame lens vs. professional grade APSC lens).

1.3.2.1. Curious thought experiment

You can easily see that a large sensor makes high lens resolutions cheap.

Imagine a pinhole camera with a 1.3 mm hole and 2.4 x 3.6 m^2 sensor (crop-factor is 0.01). With 5.1 MP such that each pixel is 1.3 mm too, i.e., the pinhole lens fully resolves the sensor. The aperture is F/3850. At a focal length of 5.0 m, this camera is 35mm-equivalent to a 50 mm F/38 lens which has its diffraction limit (Raleigh criterion) at 5.3 MP, i.e., the camera has diffraction-limited optics. If you wonder how this camera can be equivalent to a 50 mm F/38 camera but has infinite depth of field … well, if you do the math, you'll find that the hyperfocal distance is at 5 m, just where the pinhole sits ;) So yeah, it is equivalent indeed.

And the cost of a hole is … zero, nothing, nada. This is an extreme example which illustrates that lens cost decreases and ultimatively vanishes as the sensor size increases, for any given predefined image quality.

1.3.3. Defocus blur

As noted [camera equivalence], blur due to defocus increases like $\sim crop^2$!

I.e., the effect on effective resolution depending on sensor size s is:

$$MP_{focus} = \sim \mathbf{s}^{4}$$

As soon as focus accuracy is up to µm accuracy, equivalent cameras perform the same. The above formula is valid for an AF module which is (basically) shared across bodies, like Nikon D300s and D700; or Pentax K-5 and 645D.

The impact of sensor size on focus accuracy is even stronger than with lens center resolution.

> My personal opinion is that the accuracy of focus (both automatic and manual) is the strongest single argument in favour of full frame over APSC.

I.e., the required engineering precision of a 36 MP full frame AF is not more than that of an equivalent 7 MP APSC camera. To cope with that, APSC cameras must simply be stopped down more (in equivalent terms).

1.3.4. Noise

Equivalent cameras have the same level of image noise. Moreover, type-1 equivalent cameras have the same pixel noise while a type-2 equivalent camera with the larger sensor will have more pixel noise. However, pixel-noise is irrelant for a given output image where image noise is all what matters.

But the larger sensor will give access to larger equivalent apertures which render less image noise.

1.3.5. Dynamic range

Equivalent cameras have the same dynamic range.

However, the larger sensor will give access to lower equivalent ISO settings (like true ISO 75 for the Nikon D800 (DxO measurement) which would require true ISO 32 for APSC which is unavailable (or ISO 19 for FourThirds which only features ISO 132 or worse). Assuming ISO isn't artificially lowered by an ND filter or a translucent mirror, then the lowest equivalent ISO setting is directly proportional to a camera's dynamic range. This is why the D800 scores top in DxO's dynamic range ranking (featuring 14.4 EV). Note that dynamic range is also reduced by read-out noise but the most recent Exmor sensors by Sony already come very close to the physical limits in the absence of read-out noise.

Another way to look at this is by counting the overall number of electrons which can be stored on the sensor for a single image: The first order approximation is that it is proportional to the overall sensor surface.

Theoretically, a small sensor can have a high dynamic range too: Just make the silicon “thick” enough to store enough electrons in the so-called pixel wells. However, this is much more expensive than to make it larger. Because it requires a different and more difficult CMOS process.

1.4. Depth of field

Equivalent cameras have the same depth of field.

But the larger sensor will give access to larger equivalent apertures which have more shallow depth of field.

1.5. Reach

With a type-1 equivalent camera, the smaller camera will have more “reach”, i.e., the same lens will act as a longer focal length. However, type-1 equivalent cameras still have equal weight lenses for the same field of view. Adding a tele converter to the smaller sensor lens is one way of achieving the same reach with the larger sensor. The tele converter will magnify the image circle making the smaller sensor lens suitable for the larger sensor's image circle. i.e., you can use any DX lens with an 1.4x tele converter on an FX camera and fill the frame. Of course, adding a tele converter will *not* improve the image quality.

Moreover, with a type-2 equivalent camera, the larger camera will have the same “reach” because the pixel pitch will be the same.

It is the ratio of pixel-pitches, and *not* the crop-factor, which determines the “reach-factor” for a crop camera. MicroFourThird cameras don't have good reach because their pixel count is relatively low.

1.6. Viewfinder

Many people quote the bigger viewfinder image as main advantage of a larger sensor camera.

However, this isn't a fundamental advantage. A crop camera could easily be made to have a viewfinder image equally big as a full frame camera. And it would *not* be dimmer with an equivalent lens either

So, the bigger viewfinder isn't a fundamental advantage of the bigger sensor.

Still, existing cameras feature smaller viewfinders with the smaller sensor. So, vendors artifically make viewfinders less impressive than they need to be, esp. for smaller sensors. Some examples:

Camera	*viewfinder magnification* **x** *coverage*	*35-mm equivalent v.m.x c.*
Nikon D800 / D4	0.70 x	0.70 x
Nikon D800 (in DX mode)	0.70 x	0.46 x
Nikon D300 / D300s (DX)	0.94 x	0.62 x
Nikon D3200 (DX)	0.76 x	0.50 x
Nikon F5	0.75 x	0.75 x
Pentax MX	0.92 x	0.92 x

As you can see, even on today's full frame cameras, the viewfinders are made rather small compared to some classic cameras in the 70s.

Viewfinder magnification is the ratio of field of view thru the eye-piece and thru the lens, using a 50 mm lens. 35-mm *equivalent* viewfinder magnification is the ratio of field of view thru the eye-piece and thru the lens, using a 35-mm *equivalent* lens to 50 mm (33 mm for APSC).

35-mm equivalent viewfinder magnification times coverage is proportional to the virtual linear dimensions of the viewfinder image as it appears to the eye when looking thru.

The viewfinder magnification isn't limited to numbers below 1 x, it can become rather large. As is obvious with electronic viewfinders which magnify rather tiny OLED displays to rather large virtual sizes.

However, a large magnification with large (near 100%) coverage requires an ocular (eye piece) with a high eye point for the human eye to overview the entire field of view. Such oculars can be rather expensive (several hundred $) as can be seen by shopping such “wide angle” oculars for astronomical telescopes. Therefore, I believe the smaller sensor cameras have smaller virtual viewfinders only to make them more cost-effective.

Another example where bigger may mean cheaper.

2. Cost curves

We have seen that equivalent cameras produce equivalent, indistinguishable image quality if the cameras are (almost) ideal, i.e., if they are produced expensive enough. However, we have seen too that certain real-world quality aspects for a given equivalent lens or camera class are cheaper to make for a larger sensor, such as a high lens resolution or accurate focus operation or high dynamic range. On the other hand, of course, a camera with a larger sensor is more expensive in the first place, because the sensor is more expensive to make.

This means that for low image quality, the smaller sensor always wins (has lower cost) while with increasing demand on image quality, larger sensor options can become more cost efficient overall.

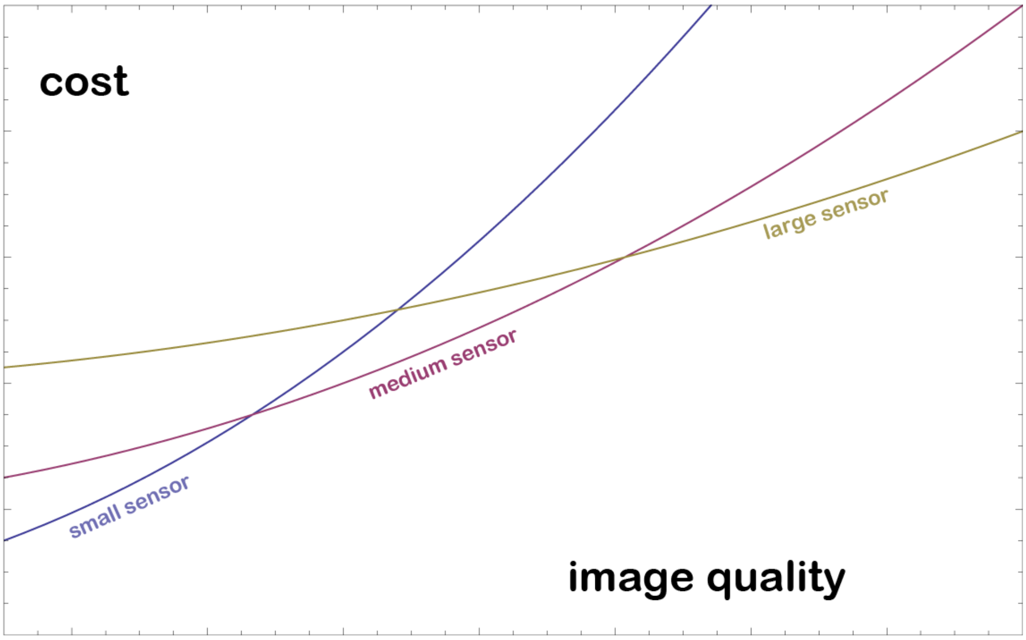

Fig. 3 Cost vs. image quality for varying sensor sizes. In theory, every image quality can be made with every sensor size by making an equivalent camera.

However, with a sensor too small, this becomes increasingly expensive such that for each given image quality, there is a sweet spot of best sensor size.

Fig. 3 illustrates how there is a sweet spot or optimum sensor size which minimizes the cost of a camera, for any given image quality. For zero image quality, the larger sensor camera is more expensive because the sensor is. For high image quality, the larger sensor camera wins because its optics and other components are cheaper to make (remember the pinhole thought experiment).

Moreover, the sweet spot moves over time as technology progresses: the sensor become cheaper making the differences in offsets smaller. While the difference in cost of optics and mechanics is typically increasing over time.

Therefore, for any given image quality, the sweet spot for sensor size increases over time.

This means there are two driving forces shifting the market up to larger sensors:

1. The moving sweet spot makes the camera with a larger-than-previous-generation sensor the cheapest to make, even if the performance and image quality is kept constant.
2. The market may demand higher image quality because the overall cost is decreasing too. This should accelerate the shift to larger sensor sizes.

Now, I observe that such a shift did not really happen in the years between 2001 and 2011: the bulk of dSLRs remained at the APSC sensor size and the bulk of P&S cameras remained at a 1/2.33” sensor size.

2.1. Supercriticality

This means the market must have moved away from its point of equilibrium. Sensor sizes have been kept smaller than technically appropriate, possibly to protect good margins in a growing and prospering market. Such a state of any system is known as *supercritical*: any small perturbation may suffice to throw it back into a state of equilibrium.

And this is what I think to see happening in 2012 (or predict for 2013 otherwise): the mobile phone camera Nokia 808 featuring an 1/1.2” sensor, the Sony RX100 featuring a 1” sensor or the Nikon D600 succeeding the D300 as a full frame rather than an APSC camera. The Pentax 645D medium format camera breaking the $10,000 barrier being another example.

Ultimately of course, we're going to see full frame SLRs to be replaced by medium format mirrorless. But that's still about another decade to go, I think.

3. Conclusion

Full frame cameras, esp. full frame digital SLRs, are a good option to obtain premium image quality.

I explained why there is a sweet spot of image quality where full frame cameras deliver the most cost-efficient solution today. And this is why their market impact must be increasing rapidly.

IMHO, this sweet spot may be expressed today as the region of between 20 and 50 *clear* MP images. Below, I think APSC still provides the better alternative and above it may be medium format. The Nikon D800 sits right in the middle of this region and this may explain why it is such a smash hit.

Moreover, I think that the region of premium image quality will remain the domain of SLRs for quite a while. Because lenses aren't that small anyway and the optical viewfinders are harder to beat (they are hard to beat anyway when it comes to low light and fast action). This means that every SLR maker will ultimately have to offer a compelling range of full frame cameras and lenses (in order to stay SLR maker). Nikon seems to understand, Canon was lucky enough to have had an early popular full frame camera but more recently, seems to miss the train. And Pentax, we'll see...