Fundamental Principles of Analytical Design

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Summary

In his 2006 offering *Beautiful Evidence*, Edward Tufte highlights what he calls the **Fundamental Principles of Analytical Design** [1]. In this short article, we illustrate Tufte's principles by analyzing the Gapminder's Foundation *Health and Wealth* data visualization (2012) [2].

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1 Background

Why do we display evidence in a report, in a newspaper article, or online? What is the fundamental goal of our charts and graphs? Tufte suggests that we present evidence to assist our thinking processes [1, p.137].

In this regard, his principles are universal – a strong argument can be made that they are dependent neither on technology nor on culture. Reasoning (and communicating our thoughts) is intertwined with our lives in a causal and dynamic multivariate Universe (the 4 dimensions of space-time making up only a small subset of available variates); whatever cognitive skills allow us to live and evolve can also be brought to bear on the presentation of evidence.

Tufte also highlights a particular symmetry to visual displays of evidence, being that **consumers should be seeking exactly what producers should be providing** (more on exactly what that is in a little bit).

Physical science displays tend to be less descriptive and verbal, and more visual and quantitative; up to now, these trends have tended to be reversed when dealing with evidence displays about human behaviour.

In spite of this, Tufte argues that his principles of analytical design can also be applied to social science and medicine. To demonstrate the universality of his principles, he describes in detail how they are applied in a visual display by **Charles Joseph Minard** (see Fig. 1).

His lengthy analysis of the image is well worth the read [1, pp.122-139] – it will not be repeated here (I must confess that the chart itself leaves me somewhat cold). Rather, I will illustrate the principles with the help of the following image from the Gapminder Foundation (see Fig. 2).

The latter image a bubble chart that plots the 2012 life expectancy, adjusted income per person in USD (log-scaled), population, and continental membership for 193 UN members and 5 other countries, using the latest available data. A high-resolution version of the image can be found on the **Gapminder website**.

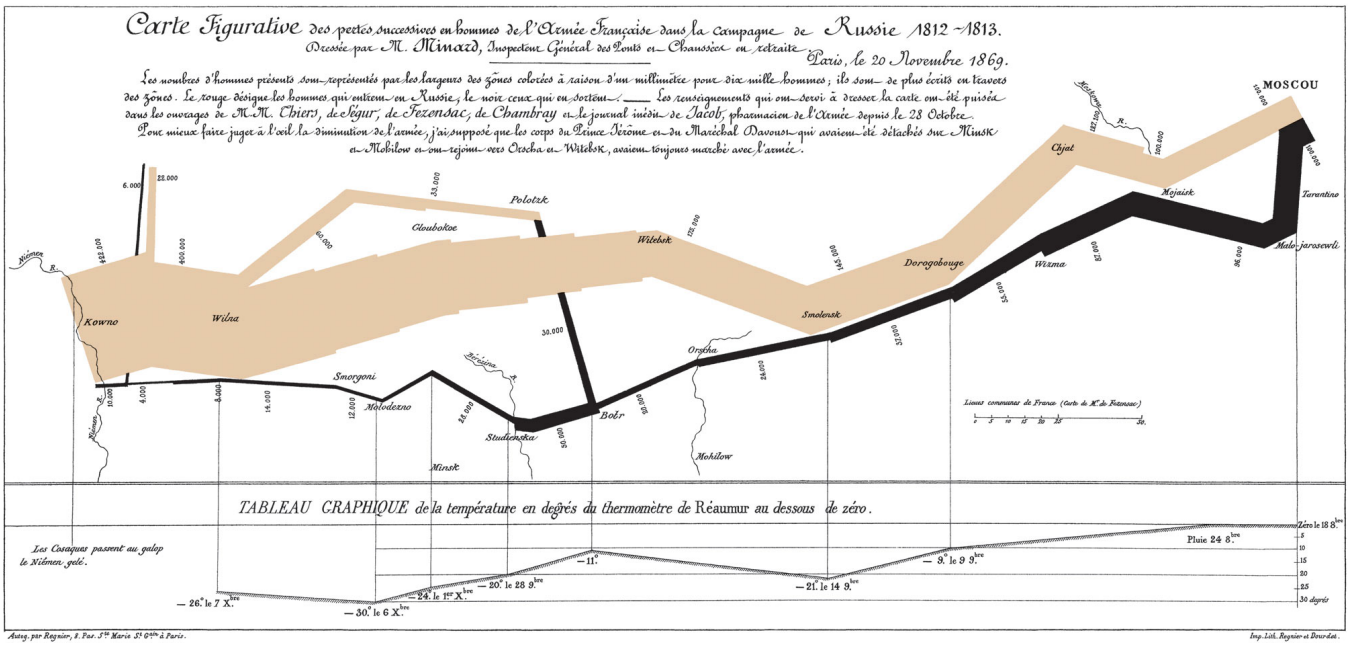


Figure 1. Carte Figurative des pertes successives en hommes de l'Armée Française dans la campagne de Russie 1812-1813, (M.Minard, 1869, [3]; indicates the number of Napoleon's troops, the distance, the temperature, the latitude and longitude, the direction of travel, and the location relative to specific dates.)

2 Fundamental Principles

Tufte identifies 6 basic properties of superior analytical charts:

- meaningful comparisons
- causal and underlying structures
- multivariate links
- integrated and relevant data
- honest documentation
- primary focus on content

2.1 Comparisons

First Principle

Show comparisons, contrasts, differences. [1, p.127]

Comparisons come in varied flavours: for instance, one could compare a

- unit at a given time against the same unit at a later time;
- unit's component against another of its components;
- unit against another unit,
- or any number of combinations of these flavours.

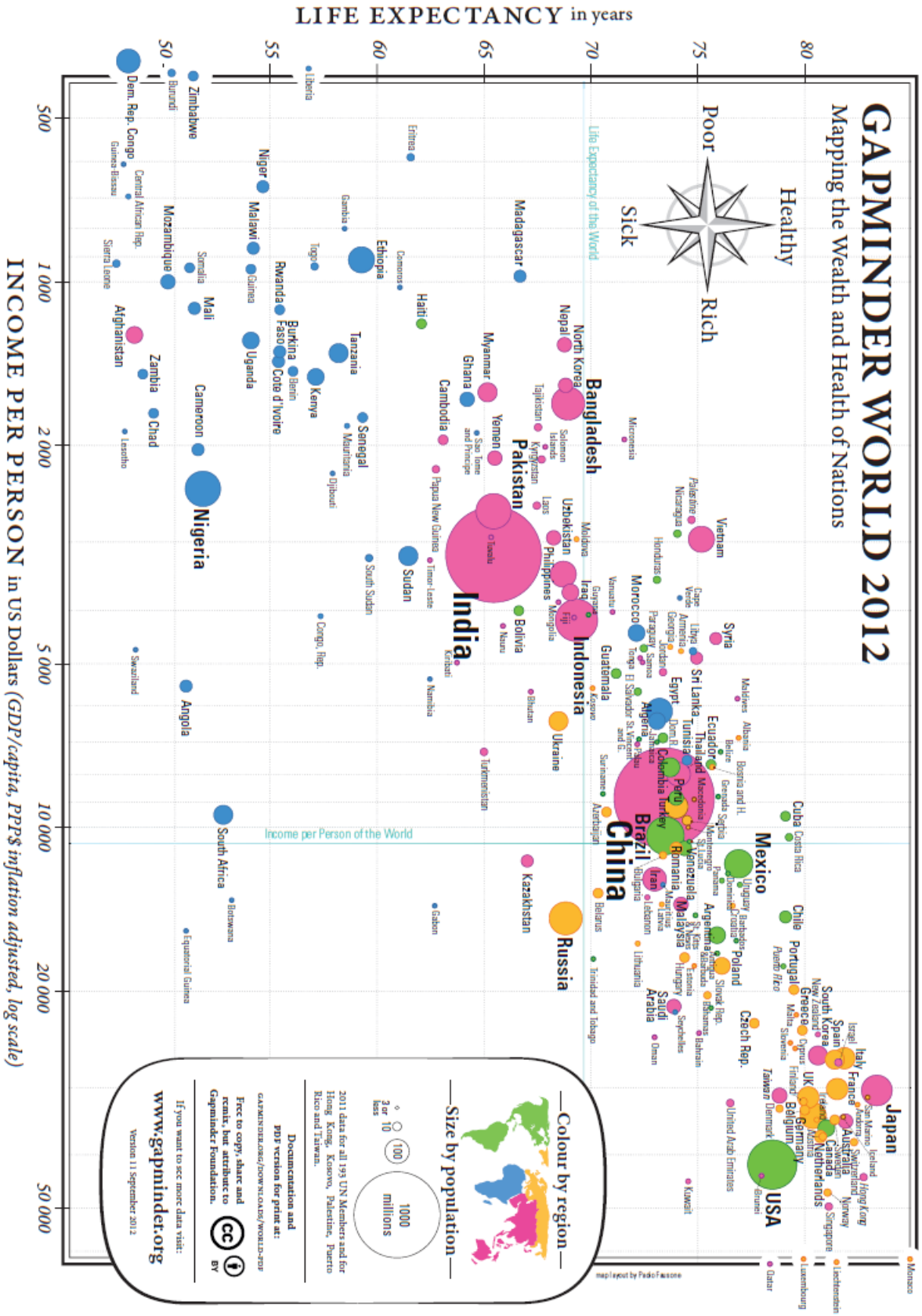


Figure 2. Life expectancy and income per capita in 2012, by nation (Gapminder Foundation)

Tufte further explains that

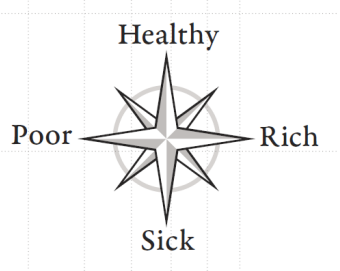
> the fundamental analytical act in statistical reasoning is to answer the question "Compared with what?" Whether we are evaluating changes over space or time, searching big data bases, adjusting and controlling for variables, designing experiments, specifying multiple regressions, or doing just about any kind of evidence-based reasoning, **the essential point is to make intelligent and appropriate comparisons** [emphasis added]. Thus, visual displays [...] should show comparisons. [1, p.127]

Not every comparison will turn out to be insightful, but avoiding comparisons altogether is equivalent to producing a useless display, built from a single datum.

Health and Wealth of Nations

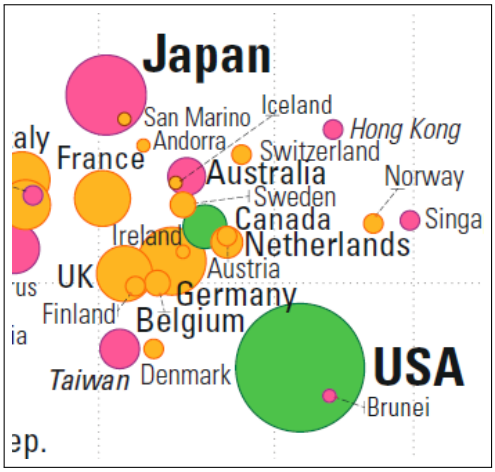
Where to begin? First, note that each bubble represents a different country, and that the location of each bubble's centre is a precise point corresponding to the country's life expectancy and its GDP per capita. The size of the bubble correlates with the country's population and its colour is linked to continental membership.

The chart's compass provides a handy tool for comparison:

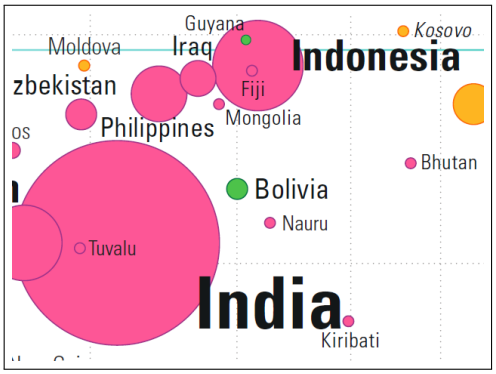


- a bubble further to the right (resp. the left) represents a wealthier (resp. poorer) country;
- a bubble further above (resp. below) represents a healthier (resp. sicker) country.

For instance, a comparison between Japan, Germany and the USA shows that Japan is healthier than Germany, which is itself healthier than the USA, as determined by life expectancy, while the USA is wealthier than Germany, which is itself wealthier than Japan, as determined by GDP per capita (see below).

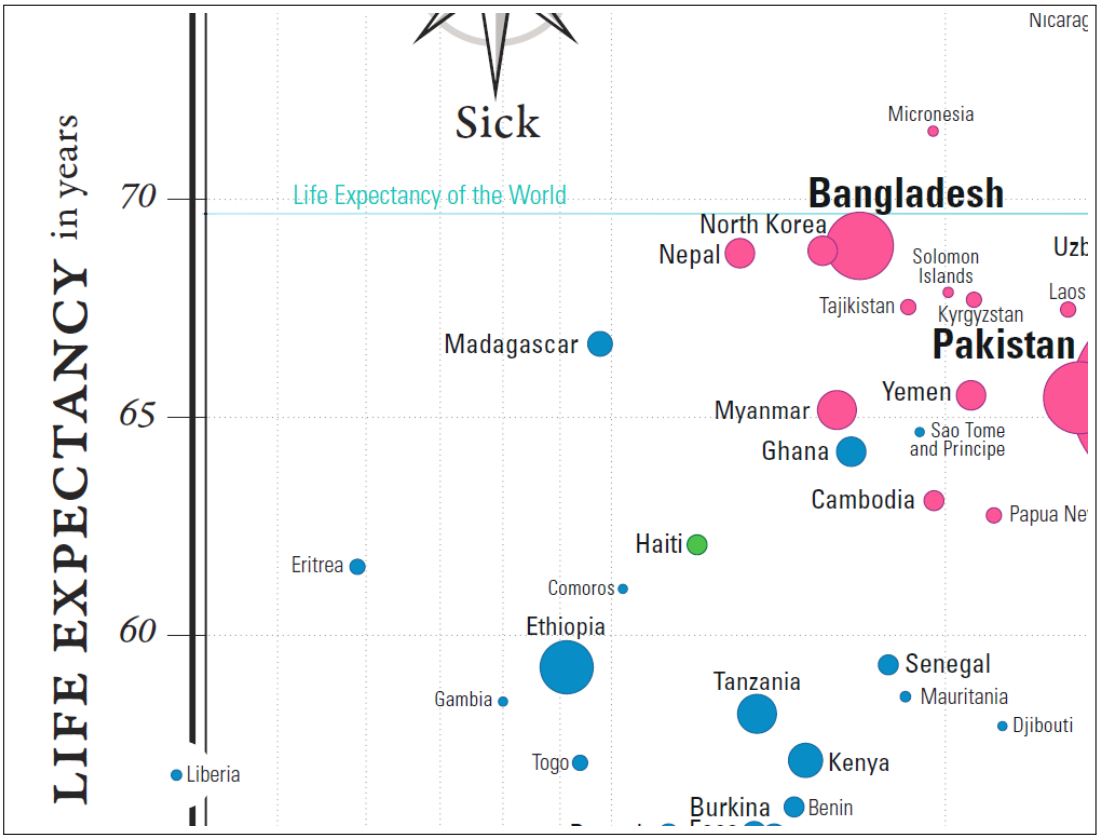


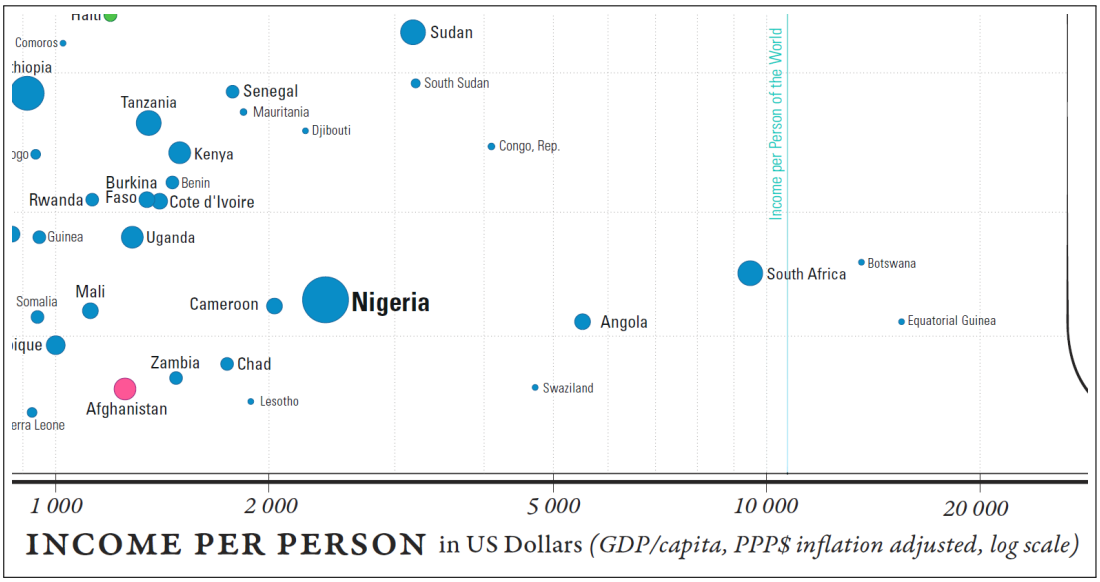
It is possible for two countries to have roughly the same health and the same wealth: consider Indonesia and Fiji, or India and Tuvalu, for instance (see below).



In each pair, the centres of both bubbles overlap: any difference in the data must be found in the bubbles' area or in their colour.

Countries can also be compared against world values for life expectancy and GDP per capita (a shade under 70 years and in the neighbourhood of $11K\$$, respectively). The world's mean life expectancy and income per person are traced in light blue (see below for life expectancy and on the next page for GDP per capita).





Wealthier, healthier, poorer, and sicker are relative terms, but we can also use them to classify the world's nations with respect to these mean values, "wealthier" now meaning "wealthier than the average country", and so on.

2.2 Causality, Mechanism, Structure, Explanation

Second Principle

Show causality, mechanism, explanation, systematic structure [1, p.128].

In essence, this is the core principle behind data visualization: the display needs to explain *something*, it needs to provide links between cause and effect.

As Tufte points out,

> often **the reason that we examine evidence is to understand causality, mechanism, dynamics, process, or systematic structure** [emphasis added]. Scientific research involves causal thinking, for Nature's laws are causal laws. [...] Reasoning about reforms and making decisions also demands causal logic. To produce the desired effects, we need to know about and govern the causes; thus "policy-thinking is and must be causality-thinking" [1, p.128], [4].

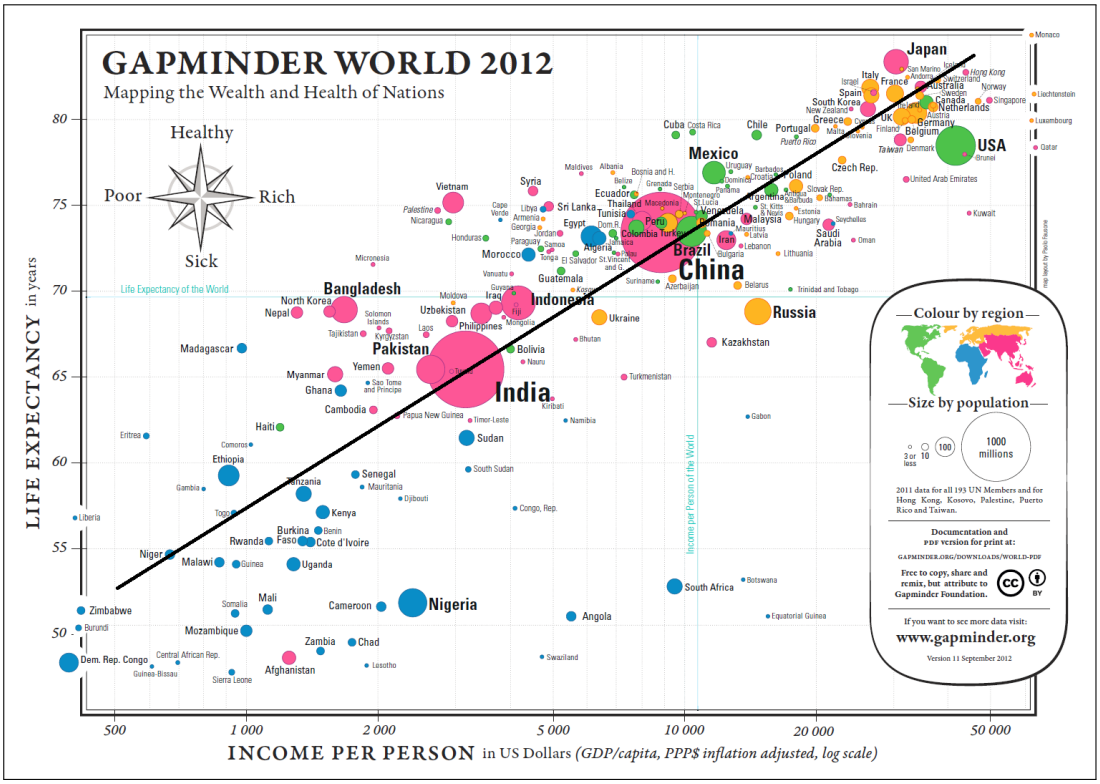
Note also that

> simply collecting data may provoke thoughts about cause and effect: measurements are inherently comparative, and comparisons promptly lead to reasoning about various sources of differences and variability [1, p.128].

Finally, if the visualization can be removed without diminishing the narrative, then that chart should, in all probability, be excluded from the final product, no matter how pretty and modern it looks, or how costly it was to produce.

Health and Wealth of Nations (continued)

At a quick glance, the relation between life expectancy and the logarithm of the income per person seems to be increasing more or less linearly. The exact parameter values are not known (and cannot be estimated analytically without the data points), but an approximate line-of-best-fit has been added in black to the figure below.

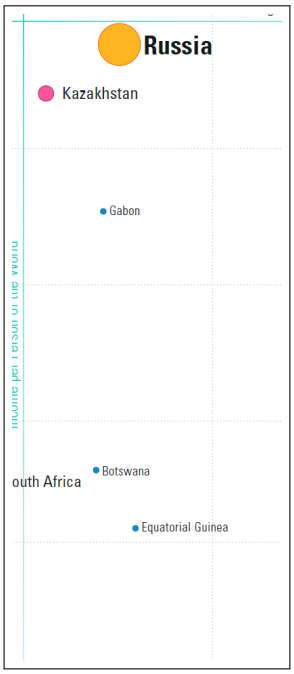


Using the points $(10000 \text{ USD}, 73.5 \text{ years})$ and $(50000 \text{ USD}, 84.5 \text{ years})$ yields a line with equation

$$\text{Life Expectancy (}\textit{in years}\text{)} \approx 6.83 \times \ln(\text{Income Per Capita (}\textit{in USD}\text{)}) + 10.55$$

The exact form of the relationship and the numerical values of the parameters are of little significance at this stage – the key insight is that wealthier countries appear to be healthier, generally, and *vice-versa*.

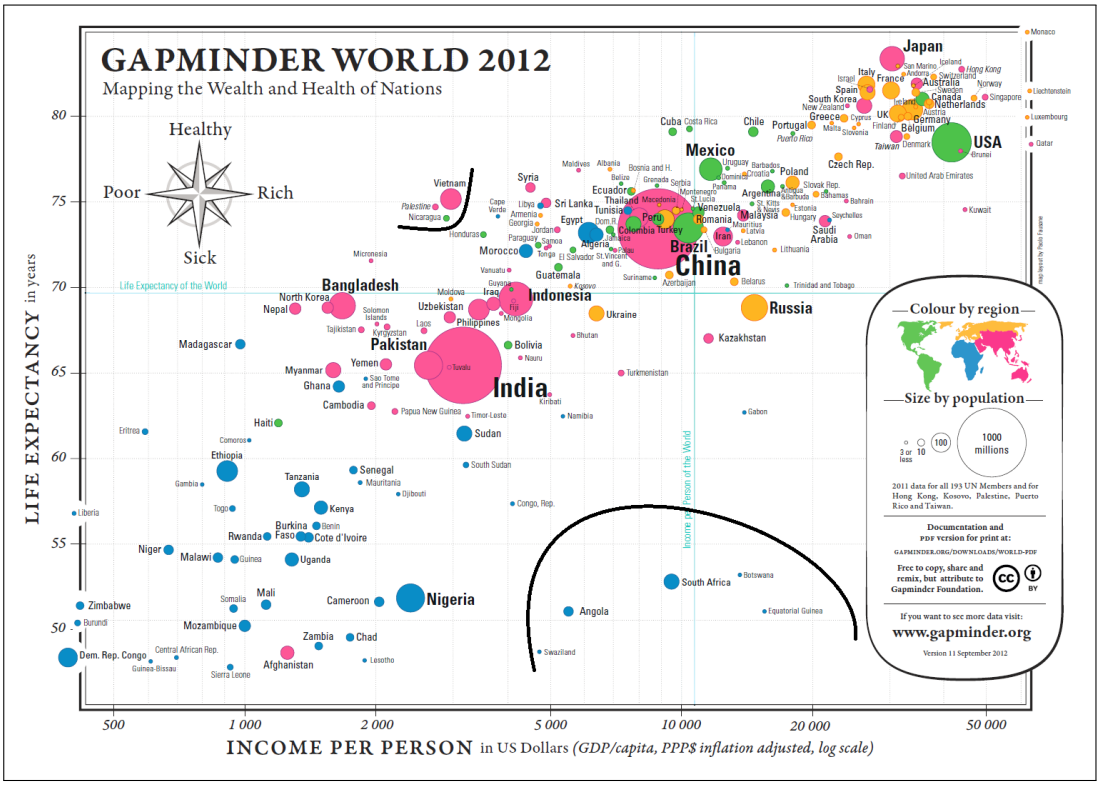
The chart also highlights an interesting feature in the data, namely that the four quadrants created by separating the data along the Earth's average life expectancy and the GDP per capita for the entire planet do not host the same patterns.



Naïvely, it might have been expected that each of the quadrants would contain about 25% of the world's countries (although the large population of China and India muddle the picture somewhat). However, one quadrant is substantially under-represented in the visualization. Should it come as a surprise that there are so few "wealthier" yet "sicker" countries? (see next image, below).

It could even be argued that Russia and Kazakhstan are in fact too near the separators to really be considered clear-cut members of the quadrant, so that the overwhelming majority of the planet's countries are found in one of only three quadrants.

In the same vein, when we consider the data visualization as a whole, there seems to be one group of outliers below the main trend, to the right, and to a lesser extent, one group above the main trend, to the left (see below).



These cry out for an explanation: South Africa, for instance, has a relatively high GDP per capita but a low life expectancy (potentially, income disparity between a poor majority and a substantially wealthier minority might help push the bubble to the right, while the lower life expectancy of the majority drives the overall life expectancy to the bottom). This brings up a crucial point about data visualization: it seems virtually certain that the racial politics

> of *apartheid* played a major role in the position of the South African outlier... but the chart emphatically DOES NOT provide a proof of that assertion. Charts suggest, but proof comes from deeper domain-specific analyses.

2.3 Multivariate Analysis

Third Principle

Show multivariate data; that is, show more than 1 or 2 variables. [1, p.130]

In an age where data collection is becoming easier by the minute, this seems like a no-brainer: why waste time on uninformative univariate plots? Indeed,

> nearly all the interesting worlds (physical, biological, imaginary, human) we seek to understand are inevitably multivariate in nature. [1, p.129]

Furthermore, as Tufte suggest,

> the analysis of cause and effect, initially bivariate, quickly becomes multivariate through such necessary elaborations as the conditions under which the causal relation holds, interaction effects, multiple causes, multiple effects, causal sequences, sources of bias, spurious correlation, sources of measurement error, competing variables, and whether the alleged cause is merely a proxy or a marker variable (see for instance, [5]). [1, p.129]

While we should not dismiss low-dimensional evidence simply because it is low-dimensional, Tufte cautions that

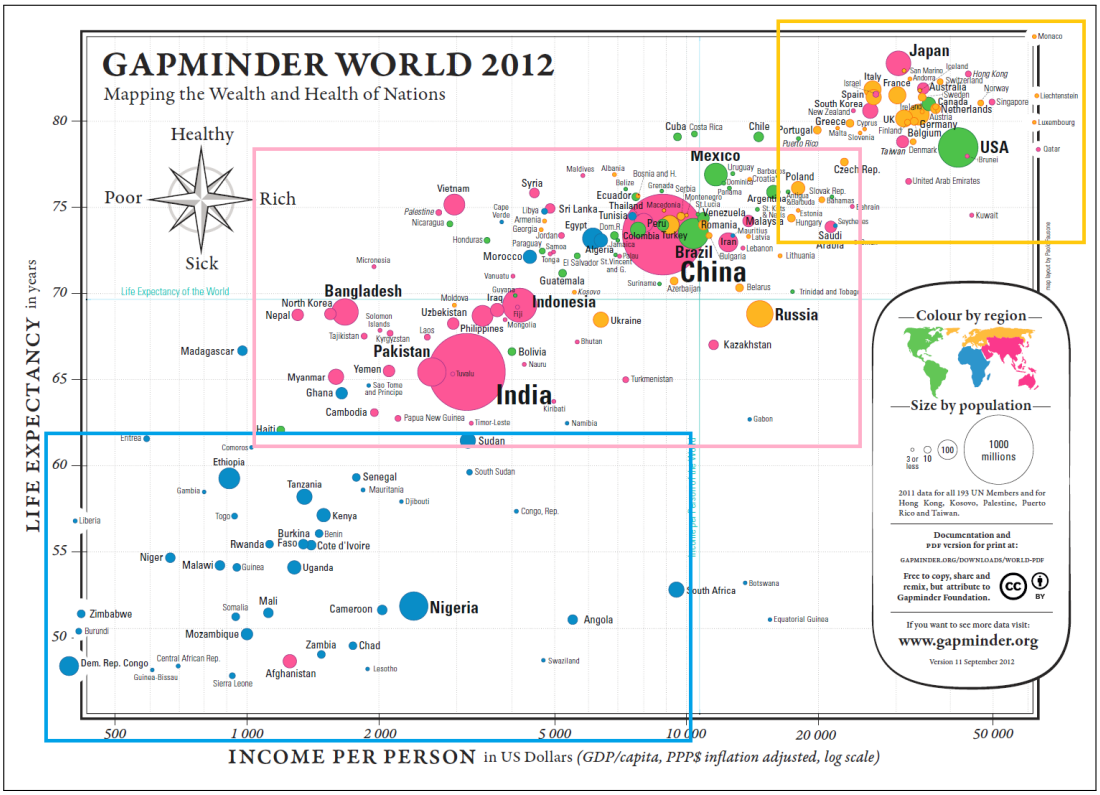
> **reasoning about evidence should not be stuck in 2 dimensions, for the world we seek to understand is profoundly multivariate** [emphasis added]. [1, p.130]

Alert readers may question the ultimate validity of this principle: after all, doesn't **Occam's Razor** warn us that "it is futile to do with more things that which can be done with fewer"? This would seem to be a fairly strong admonition to not reject low-dimensional visualizations out of hand.

This interpretation depends, of course, on what it means to "do with fewer": are we attempting to "do with **fewer**", or to "**do** with fewer"? If it's the former, then we can produce simple charts to represent the data (which quickly balloons into a multivariate meta-display), but any significant link between 3 and more variables is unlikely to be shown, which drastically reduces the explanatory power of the charts. If it's the latter, the difficulty evaporates: we simply retain as many features as are necessary to maintain the desired explanatory power.

> **Health and Wealth of Nations (continued)**
>
> Only 4 variables are represented in the display, which we could argue just barely qualifies the data as multivariate. The population size seems uncorrelated with both of the axes'

variates, unlike continental membership: there is a clear divide between the West, most of Asia, and Africa (see below). This "clustering" of the world's nations certainly fits with common wisdom about the state of the planet, which provides some level of validation for the display.



Other variables could also be considered or added, notably the year, allowing for bubble movement: one would expect that life expectancy and GDP per capita have both been increasing over time. The Gapminder Foundation's **online tool** can build charts with other variates, leading to interesting inferences and suggestions.

2.4 Integration of Evidence

Fourth Principle

Completely integrate words, numbers, images, diagrams. [1, p.131]

Data does not live in a vacuum. Tufte's approach is clear:

> the evidence doesn't care what it is – whether word, number, image. **In reasoning about substantive problems, what matters entirely is the evidence, not particular modes of evidence** [emphasis added]. [1, p.130]

The main argument is that evidence from data is better understood when it's presented with context and accompanying meta-data.

Indeed,

> **words, numbers, pictures, diagrams, graphics, charts, tables belong together** [emphasis added]. Excellent maps, which are the heart and soul of good practices in analytical graphics, routinely integrate words, numbers, line-art, grids, measurement scales. [1, p.131]

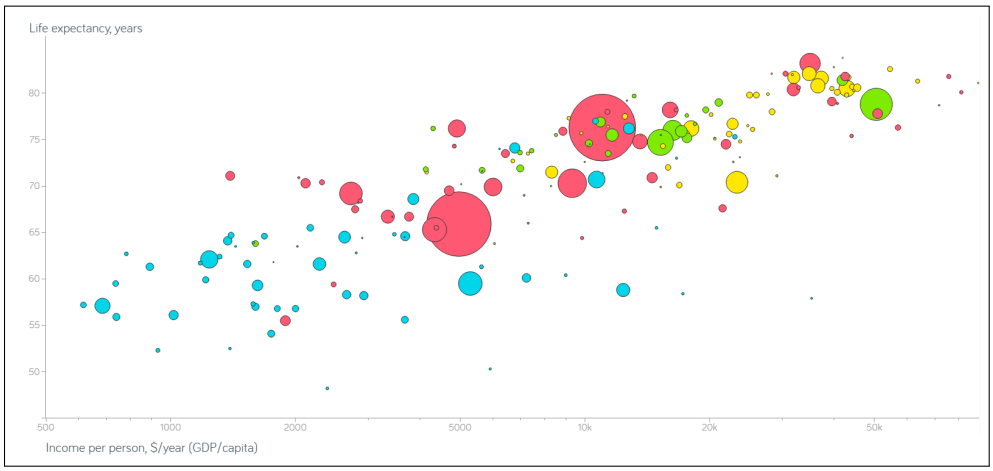
Finally, Tufte makes the point that we should think of data visualizations and data tables as elements that provide vital evidence, and as such they should be integrated in the body of the text:

> Tables of data might be thought of as paragraphs of numbers, tightly integrated with the text for convenience of reading rather than segregated at the back of a report. [...] Perhaps the number of data points may stand alone for a while, so we can get a clean look at the data, although techniques of layering and separation may simultaneously allow a clean look as well as bringing other information into the scene. [1, p.131]

When authors and researchers select a single specific method or mode of information during the inquiries, the focus switches from "can we explain what's happening?" to "can the method we selected explain what's happening?". There is an art to method selection, and experience can often suggest relevant methods, but remember that "when all one has is a hammer, everything looks like a nail": the goal should be to use whatever (and all) evidence is necessary to shed light on "what's happening". If that goal is met, it makes no difference which modes of evidence were used.

Health and Wealth of Nations (continued)

The various details attached to the chart (such as country names, font sizes, axes scale, grid, and world landmarks) provide substantial benefits when it comes to consuming the display. They may become lost in the background, with the consequence of beingtaken for granted. Compare the display obtained from (nearly) the same data, but without integration of evidence (see below).



2.5 Documentation

Fifth Principle

Thoroughly describe the evidence. Provide a detailed title, indicate the authors and sponsors, document the data sources, show complete measurement scales, point out relevant issues. [1, p.133]

We cannot always tell at a glance whether a pretty graphic speaks the truth or presents a relevant piece of information. Documented charts may provide a hint, as

> the credibility of an evidence presentation depends significantly on the quality and integrity of the authors and their data sources. Documentation is an essential mechanism of quality control for displays of evidence. **Thus authors must be named, sponsors revealed, their interests and agenda unveiled, sources described, scales labeled, details enumerated** [emphasis added]. [1, p.132]

Depending on the context, questions and items to address could include:

- What is the title/subject of the visualization?
- Who did the analysis? Who created the visualization? (if distinct from the analyst(s))
- When was the visualization published? Which version of the visualization is rendered here?
- Where did the underlying data come from? Who sponsored the display?
- What assumptions were made during data processing and clean-up?
- What colour schemes, legends, scales are in use in the chart?

It's not obvious whether all this information can fit inside a single chart in some cases. But, keeping in mind the *Principle of Integration of Evidence*, charts should not be presented in isolation in the first place, and some of the relevant information can be provided in the text, on the webpage, or in an accompanying document.

This is especially important when it comes to discussing the methodological assumptions used for data collection, processing, and analysis. An honest assessment may require sizable amounts of text, and it may not be reasonable to include that information with the display (in that case, a link to the accompanying documentation should be provided).

> Publicly attributed authorship indicates to readers that someone is taking responsibility for the analysis; conversely, the absence of names signals an evasion of responsibility. [...] **People do things, not agencies, bureaus, departments, divisions** [emphasis added]. [1, p.132-133]

Health and Wealth of Nations (continued)

The documentation of the Gapminder map is perhaps one of the best-documented chart out there. Let us see if we can answer the questions suggested above.

- **What is the title/subject of the visualization?**
  The health and wealth of nations in 2012, using the latest available data (2011).
- **Who did the analysis? Who sponsored the display? Who created the visualization?**
  The analysis was done by the Gapminder Foundation; the map layout was created by Paulo Fausone. No data regarding the sponsor is found on the chart or in the documentation. The relevant **Wikipedia article** states that "the Gapminder Foundation is a non-profit venture registered in Stockholm, Sweden, that promotes sustainable global development and achievement of the United Nations Millennium Development Goals by increased use and understanding of statistics and other information about social, economic and environmental development at local, national and global levels." It seems plausible that there is no external sponsor, but that is no certainty.
- **When was the visualization published? Which version is rendered here?**
  The 11th version of this chart was published in September 2012. It is the latest available version as of October 2016.
- **Where did the underlying data come from? What assumptions were made during data processing and clean-up?**
  Typically, the work that goes into preparing the data is swept under the carpet in favour of the visualization itself; there are no explicit source of data on this chart, for instance. However, there is a URL in the legend box that leads to **detailed information**. For most countries, life expectancy data was collected from:
  - the Human Mortality database,
  - the UN Population Division World Population Prospects,
  - files from historian James C. Riley,
  - the Human Life Table database,
  - data from diverse national statistical agencies,
  - the CIA World Fact book,
  - the World Bank, and
  - the South Sudan National Bureau of Statistics.

  Benchmark 2005 GDP data was derived via regression analysis from International Comparison Program data for 144 countries, and extended to other jurisdictions using another regression against data from
  - the UN Statistical Division,
  - Maddison Online,
  - the CIA World Fact book,and
  - estimates from the World Bank.

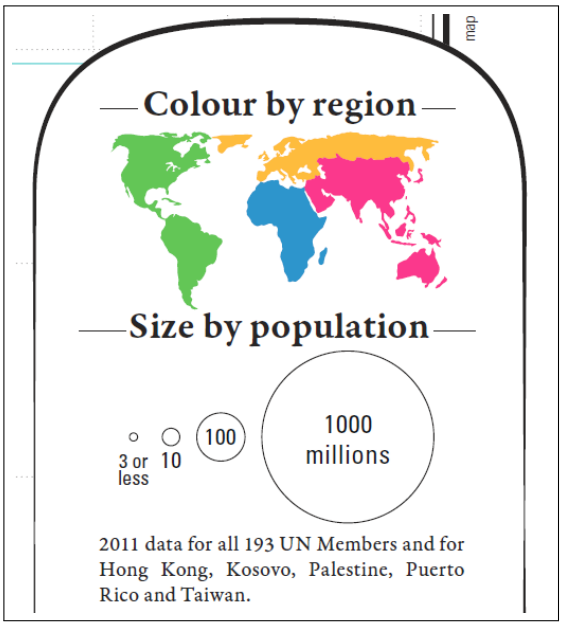
  The 2012 values were then derived from the 2005 benchmarks using long-term growth rates estimate from
  - Maddison Online,
  - Barro & Ursua,
  - the United Nations Statistical Division,
  - the Penn World Table (mark 6.2),
  - the International Monetary Fund's World Economic Outlook database,
  - the World Development Indicators,
  - Eurostat, and
  - national statistical offices or some other specific publications.

Population estimates were collated from

- the United Nations Population Division World Population Prospects,
- Maddison Online,
- Mitchell's International Historical Statistics,
- the United Nations Statistical Division,
- the US Census Bureau,
- national sources,
- undocumented sources, and
- "guesstimates".

Exact figures for countries with a population below 3 million inhabitants were not needed as this marked the lower end of the chart resolution.

- **What colour schemes, legends, scales are in use in the chart?**
  The *Legend Inset* is fairly comprehensive:



Perhaps the last item of note is that the scale of the axes differs: life expectancy is measured linearly, whereas GDP per capita is measured on a logarithmic scale.

2.6 Content Counts Most of All

Sixth Principle

Analytical presentations ultimately stand of fall depending on the quality, relevance, and integrity of their content. [1, p.136]

Any amount of time and money can be spent on graphic designers and focus groups, but

> the most effective way to improve a presentation **is to get better content** [emphasis added] [...] design devices and gimmicks cannot salvage failed content. [...] The first questions in

constructing analytical displays are not "How can this presentation use the color purple?" Not "How large must the logotype be?" Not "How can the presentation use the Interactive Virtual Cyberspace Protocol Display Technology?" Not decoration, not production technology. The first question is "**What are the content-reasoning tasks that this display is supposed to help with?**" [1, p.136]

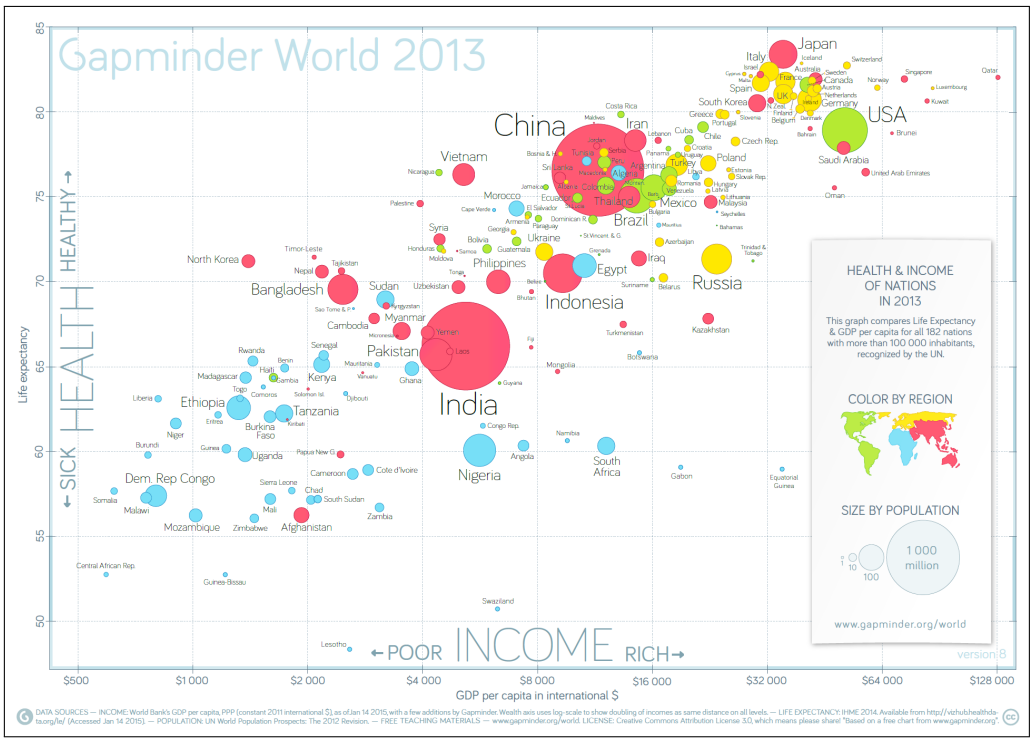
The main objective is to produce a compelling narrative, which may not necessarily be the one that was initially expected to emerge from a solid analysis of sound data. Simply speaking, the visual display should assist in explaining the situation at hand and in answering the original questions that were asked of the data.

Health and Wealth of Nations (continued)

How would we answer the following questions:

- Do we observe similar patterns every year?
- Does the shape of the relationship between life expectancy and log-GDP per capita vary continuously over time?
- Do countries ever migrate large distances in the display over short periods?
- Do exceptional events affect all countries similarly?
- What are the effects of secession or annexation?

The 2012 Health and Wealth of Nations data represent a single datum in the general space of data visualizations; in this context, getting better content means getting data for other years as well 2012.



References

[1] Tufte, E. [2006], *Beautiful Evidence*, Graphics Press.

[2] Rosling, H. [2012], *Gapminder World 2012*, Gapminder Foundation.

[3] Minard, C. J. [1869], “Carte figurative des pertes successives en hommes de l’Armée Française dans la campagne de Russie 1812-1813”.

[4] Dahl, R.A. [1965], “Cause and Effect in the Study of Politics”

[5] Hill, A.B. [1965], ”The Environment and Disease: Association or Causation?”.

Contents