CHAPTER 4

Diagrams

Spaces for Cultivating Data and Making Discoveries

4.1 This Chapter's Plan

We have seen in Chapter 3 that diagrams were central to Nadine's work, which oscillated between generating improved versions of her catalog (a table of measured and estimated galaxy properties) and representing it using various diagrams. Thus, her catalog episodically "surfaced" into a visible, inspectable form. In this chapter I build on this observation and examine how diagrams in use make private thoughts, models, and phenomena accessible intersubjectively and complex datasets surveyable. When designed and viewed in conventional ways, diagrams are bearers of tradition and culture. While this much has been discussed before, I aim to demonstrate that diagrams can also be resources for pruning datasets, for "cultivating" them, and for achieving social accountability. Diagrams materialize contexts of accountability. They are the ground on which scientists play and experiment with data. This play matters in making and assessing some discoveries – and unmaking others. As diagrams are standardized and used at many places, the resistance that their users experience can be ascribed to their efforts of being accountable to researchers elsewhere. Data, it seems, need makers and users who are members of a visual culture.

4.2 "Let's Start with the Figures": Using Diagrams to Prune a Dataset

Let us return to the last episode of Nadine's PhD project on distant galaxies in the field of the galaxy supercluster A2713, as described in Chapter 3. There she met Otfried and Peter to discuss her paper draft. This conversation marked a nexus in Nadine's project, as it assessed retrospectively if her work was properly done and, prospectively, how her intended readers – other researchers in the field – would understand it. Nadine, Otfried, and Peter have an hour or so to discuss a twenty-page draft that includes

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figures and tables. They meet in Otfried's office at a table that is soon covered with printouts, handwritten notes, plots, notebooks, pencils, a ruler, and a pocket calculator. As so often when scientists talk about science, they decide to focus on the figures first:[1]

Transcript 4.1

1 Otfried: I would start with the big issues … because … ehm
2 Peter: Then I need to go through and think about them and sort them
3 Otfried: and then later I would go to the nitty gritty … what is in the introduction … what is … for instance with this histogram
4 Peter: Let's start with the histograms … let's start with the figures anyway … let's start with the figures
5 Otfried: Exactly … which you criticized!
6 Peter: Right. (…)

Diagrams are immediately visible to all participants in this conversation. They focus attention and can be pointed at. They are easier to survey than the twenty pages of Nadine's draft, not to mention the catalog or the tables used to generate the plots. The diagrams in Nadine's draft represent measurements, whereas the text describes their interpretation.

The first figure in Nadine's draft is a $n(z)$ plot, a histogram that describes her sample by representing the number of detected galaxies (n) in bins of increasing redshift (z) (Figure 4.1). This is the diagram that Peter is most concerned about. Prior to the meeting, he had annotated his printed copy with probing questions ("where did these go?," "fit plausible?," "selection too deep?," "really??," "m–z?") that he addresses in the discussion that follows.

Transcript 4.2

6 Peter: Right. So when I looked at this histogram ((*Figure 4.1*)) I was frightened … because … I thought … if that's the universe … we've not known about it before … so probably it is not the universe … and that spells trouble. And I thought there are two alternative interpretations for this. And what I am specifically … concerned about is this dip … right? ((*He draws circles centering on the two peaks visible in the histogram, and connects them by tracing the histogram's depression in between; feature A in Figure 4.1*))
7 Nadine: Mm hm
8 Peter: where normally … in exactly that place there should be something like that ((*He sketches feature B in Figure 4.1*))
9 Nadine: Mm hm

[1] See the Appendix for a complete list of the transcription conventions adopted.

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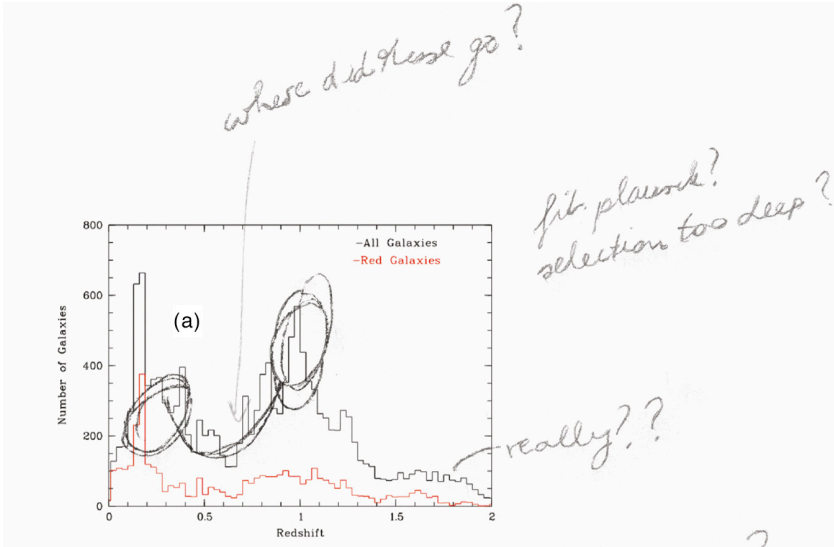


Fig. 1.— *Histogram of the photometric redshift distribution for 14286 galaxies with H<21.7 between 0<z<2 in the [redacted]-field (black) among which the distribution of 3943 red galaxies as defined by* $(U_{280}-V) > (U_{280}-V)_{lim}$ *see Eq. 5 (red)*

Figure 4.1 Histogram in Nadine's draft manuscript, showing the number of galaxies as a function of redshift for all objects detected in the A2713 field. This printout includes Peter's handwritten notes as made prior to the group meeting (unlabeled) as well as the marks he added during the discussion with Nadine and Otfried (labeled A and B). See Transcript 4.2.
Note: The online version shows the colors of the original figure.

10 Peter: So I thought there is two possibilities. One possibility … the more likely one … ehhm … because … there is a common mistake that has happened to myself a lot of times and to various other people plotting such things various times … is to choose a magnitude cut at which the sample is not complete.

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11 Nadine: Mm hm
12 Peter: And so the shape that you get for the $n(z)$ is the original shape of the $n(z)$ in the universe multiplied by the completeness function … and if you go just deep enough almost all that you see is the completeness function itself.
13 Nadine: Mm hm
14 Peter: So you can't trust the structure anymore to mean something about the universe because it means something about your magnitude cut
15 Nadine: Mm hm

By looking at the diagram and seeing "the universe," Peter acknowledges the processed data's high externality: these are calibrated and presented as instrument-independent measures.[2] Peter abstracts the shape of Nadine's histogram with the marks that I labeled A. This dip troubles him, as it conflicts with what one would expect from observing a homogenous distribution of galaxies with a detector of limited sensitivity. A deep field survey defines a cone that reaches out from Earth into space and widens with increasing redshift and distance. If galaxies were distributed homogenously in space, this so-called light cone should contain increasingly more galaxies per redshift bin as we move to higher redshifts. But after reaching a maximum at a certain redshift, the number of detected galaxies per redshift bin should ultimately decline, since these distant galaxies appear fainter and eventually fall below the survey's sensitivity limit. Peter sketches this expected pattern (which I have labeled feature B in Figure 4.1).

Alas, this is not what Nadine's histogram looks like. Where Peter expects a peak (B) there is a dip (A), whose depth seems like a measure of how concerning it is to him. Peter and Otfried disagree on whether this dip represents an underdensity of galaxies between redshift 0.3 and 0.9. Otfried believes that there is such a "hole in the universe." Peter rather suspects that the dip hints at an issue with the completeness of Nadine's sample, that is, which fraction of galaxies at a certain redshift the survey detects and includes in its catalog and which fraction it misses – causing a biased sample. Largely an onlooker, Nadine contributes affirmative utterances ("Mm hm") to the conversation.

Peter explains that a simple way to deal with the sample's incompleteness would be to define a "conservative" magnitude cut and include only

[2] See Chapter 3 for a discussion of Pinch's (1985) notions of externality and evidential specificity.

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objects from the sample that are brighter than this limit. However, by doing so one would discard the sample's many faint galaxies, which are most interesting for Nadine's study. Peter, Otfried, and Nadine want to include as many objects in the sample as possible while not corrupting the signal and harming the team's credibility with readers:

Transcript 4.3

58 Peter: So the question is … what do you want to show … actually … what information do you want to convey … hence … what do you need to plot … hence … what do you need to look out for … for not plotting something that then looks fishy?
59 Nadine: Mm hm
60 Otfried: Yeah … exactly
61 Peter: Ehm … but this … as it is … as just a sort of global n(z) of your dataset is dominated by incompleteness issues … rather than the physical shape of the histogram … invites people to … either jump on you … or throw it away
62 Nadine: Mm hm

Thus far, this discussion has focused on Otfried's and Peter's printed and annotated copies of Nadine's draft. But now Peter uses his laptop computer to generate plots that illustrate the issues involved, using, however, not Nadine's latest "optical plus near-infrared" catalog, but Peter's older "optical-only" catalog. Peter prepares a scatterplot that shows the redshifts of galaxies over their red (R band) magnitudes, from 17 to 25 mag (Figure 4.2, fainter objects have larger magnitudes). It is useful for interpreting Nadine's histogram, which omits magnitude information:

Transcript 4.4

131 Peter: This plot … probably makes clear what we are talking about
132 Nadine: ((*points to the dark horizontal feature that spans almost the entire width of the diagram near its bottom; Figure 4.2*))
This is A2713?
133 Peter: This is A2713
134 Nadine: Yeah yeah … 24.5 ((*mag*)) is here … and we have the hole there
135 Peter: Yeah … and that is caused by completeness … So if you look at the bright
136 Otfried: That's a good plot … yeah
137 Peter: That's here … and then things fan out … structures fan out and get broader … and more points as you go fainter … this is why they look thicker

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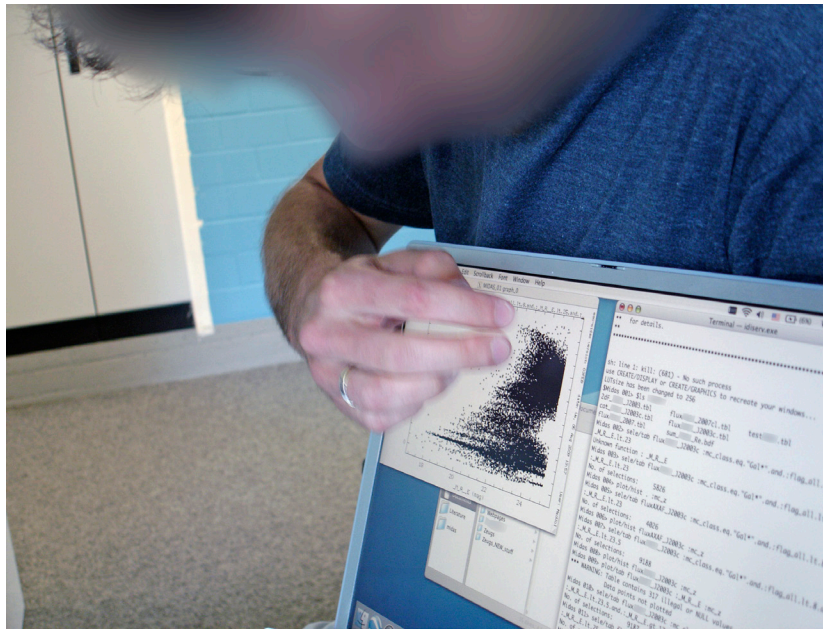


Figure 4.2 Peter explains a scatterplot that shows the redshifts of galaxies (vertical axis) over their red (R band) magnitudes (horizontal axis). See Transcript 4.4. (Photograph: Götz Hoeppe)
Note: The online version shows the colors of the original figure.

138	Otfried:	This plot is perfect
139	Peter:	also fanning out with a bit of a redshift error … And so … if you look at … this part of the plot … higher luminosities … everything is filled
140	Nadine:	Mm hm
141	Peter:	except for a few voids … right … because of the ((*galaxy*)) clusters or things like that
142	Otfried:	Mm hm
143	Nadine:	Then it's thinning out
144	Peter:	But … it already starts thinning out at 23 ((*mag*)) point and a bit … and you can make it more quantitative … but the plot illustrates it … There is a hole caused by incompleteness
145	Nadine:	Mm hm
146	Peter:	And most galaxies of this whole plot … this is 35.000 galaxies … and 90 percent of them are in this section … between 23 ((*mag*)) and 25 ((*mag*))
147	Nadine:	Mm hm

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148 Peter: So almost all galaxies live here … and hence the hole becomes very prominent. It is not just a second-order correction … but it just booms through the histogram

As is typical for astronomical surveys, Nadine's catalog is more complete for brighter objects than for faint ones (which tend to be more distant). Peter's plot reminds Otfried and Nadine of how close to the detection limit most galaxies in the sample are (line 146), making sample completeness an issue. Peter argues that errors of the redshift estimation algorithm would also affect the distribution of galaxies in his plot and that these effects conspire for galaxies to cluster in the figure's upper right and lower right parts (the "two big bumps"; Transcript 4.5, line 184). Otfried agrees with this interpretation and concedes defeat, giving up on his claim that there is a "hole in the universe" in the field at this redshift range.

With the completeness issue confirmed, the challenge is how to use as many of the detected galaxies as possible for the analysis while keeping the sample sufficiently complete. Peter asks Nadine to prepare a scatterplot from her "optical plus near-infrared" catalog akin to the one that he made using his "optical-only" catalog and explore it in half-magnitude bins to recognize at which magnitude the artifactual "bumps" dominate the histogram.

Transcript 4.5

184 Peter: If you do the histogram … for example … cut at 20.5 ((*mag*)) and then separately 20.5 ((*mag*)) to 21.5 ((*mag*)) … maybe this shows two big bumps and that shows more of a redshift structure. It could be all in the last magnitude bin where it comes from.

185 Otfried: Yeah yeah that's ( )

186 Peter: So one needs to play with these plots to see.

For Peter, "play" is an exploration using the histogram and the scatterplot to distinguish between artifactual "bumps" and real "redshift structure." He illustrates how this can be done by blocking parts of the diagram with one hand (Figure 4.3). Doing so involves making visual assessments:

Transcript 4.6

226 Peter: What I am saying is … because we don't know what the completeness is … and we don't have a good handle to produce a reliable completeness map on the spot … we could try to estimate completeness on the basis of the

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Figure 4.3 Peter demonstrates how Nadine may use the scatterplot to estimate the completeness of her galaxy catalog. See Transcripts 4.5 and 4.6. (Photograph: Götz Hoeppe)
Note: The online version shows the colors of the original figure.

> credibility of the histogram to your eye … So you plot these histograms … as long as they look healthy … at brighter magnitudes … you say "Everything that I know tells me that this is a reasonable histogram … so I should believe it." … And at some point it looks fishy and then you say "I have reasons not to believe that this is the universe." And then it is a judgment call where you make the cut.

Distinguishing between what looks "fishy" and what looks "healthy" in the histogram and the magnitude-redshift plot draws on visual skills specific to those who make photometric redshift surveys of galaxies. It requires an ability to assess "horizontal bands" of points that may be galaxy clusters, structures "fanning out" due to redshift errors, and "bumps" that may be due to redshift focusing, an artifact of the photometric redshift technique (see Chapter 3).

Whereas Otfried and others had previously guided Nadine to use diagrams to recognize mistakes and correct them, here Peter teaches her to use a diagram to "prune" her sample, taking out what would introduce biases into her sample. We may call this a "cultivation" of her dataset, for not only

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does this work make use of conventional diagram formats as well as conventional practices and units of measurement, such as astronomical magnitudes and colors. Their competent assessment also dwells on scientists' membership in an epistemic community, as suggested by Peter's references to other astronomers' evaluations of their work.[3] Embedded in scientists' uses, diagrams are a means for bringing data into a specific cultural realm. In the end, the sample used in the published paper consists of 10.692 galaxies instead of the 31.747 galaxies in Nadine's deep H band catalog. Besides their use in pruning the dataset, it was through their shared availability in this meeting that these diagrams became resources for instruction, accomplished agreements, and authorization. After all, Otfried (as Nadine's supervisor) had initially disagreed with Peter on how to interpret the $n(z)$ histogram, but changed his mind, affecting what Nadine had to do next.

By choosing to "look at the figures first," Peter and Otfried decided to use Nadine's draft in the way many scientists access the literature. In a manual advising graduate students on how to prepare graphs that Johns Hopkins University astronomy professor Nadia Zakamska posts on her website, we read:

> Figures are probably the most important part of the scientific paper: many readers of your paper will likely read the abstract and glance at the figures to decide whether the paper is worth reading / citing. Therefore, good selection and good presentation of figures is of outmost importance in conveying your results.

Continuing, Zakamska insists that "making figures is a major part [of] your overall research workflow." She adds remarks that point to the challenges that Nadine faced in her project:

> Do your figures make sense? Before showing your figures to anybody, ask yourself whether they make sense. Are your luminosities / masses / sizes reasonable, or orders of magnitude off? (If they are, this is a bug, not a new kind of astronomical object.) If your scatter plot is trending upwards, what would this mean and does that make sense? Interpreting your figures is often exactly what your research is about. Testing your figures with other figures will make you more confident of your results.[4]

Working out whether figures make sense is a continuing learning experience for scientists, restricted not only to novices like Nadine, but including senior scientists like Otfried, whom Peter convinced through his skilled use

[3] Note Sacks' (1992, vol. 1, 226–228, 245) remarks on "culture" as members' apparatus for doing and recognizing activities. See also Pinel and Svendsen (2024) on "domesticating data."

[4] zakamska.johnshopkins.edu/COMPUTING/graph_guide.html (accessed July 7, 2025).

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of diagrams that there is no hole in the universe in the region they pondered. Note that Zakamska, in mentioning luminosities, masses, and sizes, refers to the absolute physical properties of objects and thus to data of high externality (Pinch 1985). Brought into the realm of known and previously agreed-upon phenomena, the plausibility of data can be assessed more easily.[5]

4.3 Thinking and Working in Diagrammatic Spaces

In the diagrams that Nadine, Peter, and Otfried make and discuss, an enormous amount of information – redshifts and magnitudes of thousands of galaxies – is condensed into a two-dimensional space on less than a single letter-sized page. Nadine can print these diagrams and place them on the table in their midst. Participants in the discussion can point to details and agree on what they see.[6] Diagrams are "fields for interaction" (Alač 2011). They literally enable discussants to "get on the same page." Of course, Nadine, Peter, and Otfried do not only point at their diagrams – they talk along with the pointing.[7] Doing so aids them in agreeing, prompting questions, eliciting requests for clarification, and expressing disagreement.

Then there is the operability of diagrams. Diagrams do not merely *show* something – one can *do* things with them, *operate* with them. Thus, by adding hand-drawn shapes to Nadine's histogram (Figure 4.1), Peter can abstract what he sees in it to illustrate a contrast with his expectations. By sequentially hiding parts of the scatterplot that he generated with his laptop computer, Peter can reason about, and demonstrate, what causes the dip in Nadine's histogram. This operability dwells on diagrams' curious "double life" in which the concreteness of their flat surface coalesces with an abstract space (Krämer 2022). When we point at the surface of a diagram, we often point at the material and the abstract at the same time.[8]

[5] See the discussion in Chapter 3 on calibration.

[6] In some ways this summarizes Latour's (1986) notion of "immutable mobiles." How essential diagrams are to interpretations of data is illustrated, for example, by Anscombe's (1973) famous quartet of four sets of points in a plane that, despite identical averages, linear regression line slope, error of this slope, and regression coefficients, suggest quite different functional relations (see also Tufte 1983, 13–14; Sainani 2016). Pearson (1956), Tukey (1962), and Tukey and Wilk (1966) provide influential early statements on visualization in data analysis. See Hullman and Gelman (2021) for a historical review.

[7] Enfield and Sidnell (2022, 107) note that when paired with pointing, "language becomes both an instrument and an object of accountability."

[8] Husserl (1970 [1954]) claimed that science is moving toward evermore abstract accounts of nature, but the embodiment and materiality of making and using diagrams implies that a move toward abstraction is not a one-way road: "Abstraction and concretion intertwine, they complement each other" (Krämer 2014, 347).

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Many diagrams are the result of communal agreement and tradition: they are conventional. This includes that time is usually plotted along the x-axis, advancing to the right, and that north is shown at the top of most maps.[9] Nadine's work progressed from using photographic pixel exposures to individual objects' spectral energy distributions (SEDs) to representations of statistical properties of galaxy populations (cf. Figures 3.3, 3.8, and 3.9). These diagrams are specific to astronomy and common in galaxy evolution studies. Interpreting them properly is an acquired skill. Many researchers are experienced viewers and users of such diagrams, and this makes these diagrams resources for social accountability, as I will examine later in this chapter.

In Nadine's work, the SED of a single galaxy (such as in Figures 3.3 and 4.5b) is meaningful and potentially interesting, but, to represent a galaxy population's properties in a scatterplot,[10] the complexity of SED shapes must be reduced.[11] One means to do so is to define what astronomers refer to as colors. This notion is based on our visual perception, where, for example, an object looks blue if it radiates or reflects more light of visible short wavelengths than of longer wavelengths. In astronomy, colors are defined as the ratio of the flux density ("brightness") measured in different wavebands. Since magnitudes are defined as a logarithm of flux density, colors are the difference of magnitudes in two wavebands.[12] The color I – J is the difference of flux measured in the I and J bands. Thus defined, a color picks out one of the many bits of information contained in a SED.[13]

Well-chosen color differences can be suited to represent important properties of stellar and galactic populations. Color-magnitude diagrams (in which the brightness of objects is plotted over a characteristic color; see Figure 4.4) and color-color diagrams (in which measurements of two

[9] As Espeland and Stevens (2008, 424) point out, popular primers on graphical representation, like Tufte's (1983) *The Visual Display of Quantitative Information*, present lessons that are both technical and normative. Norms are relative to epistemic communities. In diagrams pertaining to cosmology and galaxy evolution, time is commonly plotted along the x-axis, but advancing to the left (since redshift – an observable – increases to the right and correlates with lookback time).

[10] Friendly and Wainer (2021, 121) argue that scatterplots, in which two different measurements of objects are plotted on perpendicular axes, "may be considered the most versatile and generally useful invention in the entire history of statistical graphics." See also Sainani (2016). In work with large datasets, density plots like Figure 4.4 are increasingly popular.

[11] This selection always comes along with a reduction of information. The ca. 35,000 galaxies represented in Figures 4.2 and 4.3, and the radiation they emit, have many other features besides their R band magnitudes and redshifts.

[12] This is because the logarithm of a fraction is the logarithm of the argument in the nominator minus the logarithm of the argument in the denominator.

[13] As colors reduce the complexity of data at the cost of a loss of transmitted information, they can be conceived as an example of a history of the compression of information using media that Sterne (2012) describes.

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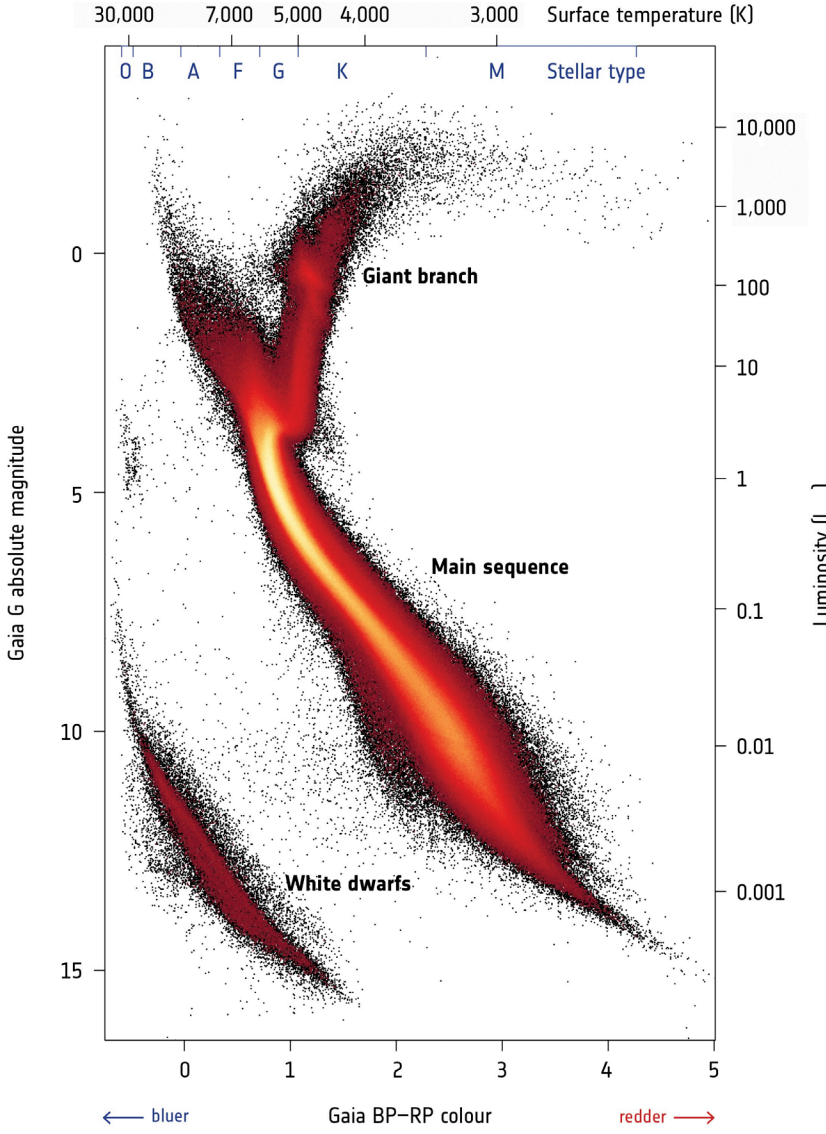


Figure 4.4 Hertzsprung–Russell Diagram of four million stars from measurements of the European Space Agency's Gaia spacecraft. Shown are the absolute magnitudes (a measure of luminosity) as a function of color (the ratio of flux measured in two optical wavebands). Here the scale does not represent the stars' physical colors but is a measure of the density of stars in the diagram: black dots represent individual stars, while shades of gray correspond to an increasing density of stars in the diagram. (© ESA/Gaia/DPAC 2018) Note: The online version shows the colors of the original figure.

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different colors of stars or galaxies are plotted against each other, say I – J vs. J – H; see Figure 4.5a) reveal that measurements of stars and galaxies are not distributed randomly in these diagrammatic spaces. They cluster in "sequences," "branches," and "clouds," but seem lacking in "valleys" and "deserts." Astronomers interpret these distributions as clues to the effects of mass, chemical composition, evolutionary stage, and environment.[14] These diagrams mark representational spaces in and through which objects of scientific discourse are defined. As Michael Lynch and Steve Woolgar (1990, 13) argue, scientific objects and representations are "inextricably connected."[15] Diagrams materialize contexts of accountability (cf. Chapter 3). Diagrammatical accountabilities are social accountabilities.

Note, eventually, how sketches on paper and other media matter to discussions of diagrams and further computational uses of data. These include Peter's sketches in his printed copy of Nadine's draft (Figure 4.1) and Otfried's blackboard sketches (cf. Figure 5.4). Such sketches are often transient, wiped off the blackboard or discarded in a paper bin after their use in interaction.[16]

4.4 "Weird Objects in Color-Color Space": Discoveries as Resistance in Diagrams

While the dip in Nadine's $n(z)$ histogram inspired Otfried to argue for a "hole in the universe," the diagrams that Peter generated on his laptop computer made this interpretation unviable. Loosely speaking, the dip did not resist these researchers' scrutiny. Conversely, it seems that researchers would accept a discovery claim only when an anomalous feature in diagrammatic space resists efforts of its normalization or removal.

Let us examine this point further by considering a serendipitous, data-driven discovery in which the use of diagrams was critical. This episode

[14] The most widely known stellar color-magnitude diagram in astronomy is the Hertzsprung–Russell Diagram (Figure 4.4). Named after two early twentieth-century scientists, all astronomy students encounter it in their training and often use it to learn to make assessments of sameness, difference, and "reasonable agreement" (Kuhn 1961). See Spence and Garrison (1993) as well as Friendly and Wainer (2021, 149–151).

[15] Among a large literature, see Lynch (1985b) and Rheinberger (1997, 102–113) on representational spaces, Larkin and Simon (1987) as well as Alač (2011) on diagrammatic reasoning, and Wimsatt (1990) and de Regt (2017) on the use of visualizations for scientific understanding.

[16] As Ochs et al. (1994) observe, "contingently transient visual representations (…) are nevertheless an important means by which physicists work through problems of understanding and come to a consensus on matters of interpretation." It is possible to regard such sketches as continuous with scientists' gestures (Myers 2015).

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focuses on the work of Arjen van der Wel, in 2011 a postdoctoral scholar and member of the Cosmic Assembly Near-IR Deep Extragalactic Legacy Survey (CANDELS) collaboration. CANDELS was an international team of researchers that used WFC3 (Wide-Field Camera 3), then a new camera on the Hubble Space Telescope (HST), to add deep near-infrared exposures in three wavebands (the I, J, and H bands) to existing data of GOODS-South, a much-observed deep field in the southern sky. In early 2011, the first CANDELS galaxy catalog of 34,930 objects became available to its team members.[17] Van der Wel used it to inspect what these new data could reveal about old massive galaxies at redshift 2, a class of objects that he had studied before and was now trying to examine at a higher angular resolution. To identify candidate objects, he searched the new catalog for entries with notable Balmer breaks, a marked discontinuity in the spectral continuum, which, for redshift 2 galaxies, is found between the I and J bands. Thus, van der Wel first selected objects of certain I – J colors from the catalog and then added more data, including the J – H colors, to assess their viability as candidate old massive galaxies at redshift 2. In an interview six years later, he reflects on this experience. A glossary of key terms follows the transcript (see Box 4.1).

Transcript 4.7

1 Arjen van der Wel: I was looking for old galaxies … old massive galaxies that also have a jump in … say … I – J. And then … that is the Balmer break. It was the first time we had these data that we could … So at redshift 2 we knew about old galaxies. But with this new camera … the WFC3 on Hubble ((*Space Telescope*)) … it was the first time we could get good insights into their structure and morphology. The previous camera NICMOS had some data … but this ((*WFC3*)) was clearly the next big thing. With the initial dataset I was just curious … what they would look like. So I didn't have SED fits or anything yet … this was just a photometric catalog. So I tried this I – J color where galaxies in this redshift range around 2 would be red … and then the J – H … the redder color … should be pretty blue … again … because SEDs are supposed to look like that.

And then I found these things that were way too blue in J – H. So the SED would look like this

[17] A refined version of this catalog was later published as Guo et al. (2013).

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((draws into the air with his hand: a descending line with one peak)). It didn't look like that *((draws into the air with his hand: a descending line without the peak, but a drop at a certain point, indicating the Balmer break))*. I thought that must be a mistake. So I started looking into these objects. It's not a sensible … it is not a sensible SED. But there was nothing wrong with the photometry. So I looked at the images to see if there is something there. Yes … it's fainter ((*laughs*)) to the surrounding … that's where the light comes from. But now there is forty of them in the entire field.

2 Götz: So that was all first in the catalog? You didn't look at the images at first?

3 Arjen van der Wel: First the catalog and then the images … to see if there is something wrong with the photometry … right? If they all live on the edge of the image or if they all live next to a bright star … right? Okay. You look at the images … and it's … Okay that's why these things are there and they're fake. Could also be the initial catalog with this new data … so who knows what is wrong with it … right? But it looked like they were real … so then at some point you start thinking of outlandish explanations … including that it could be an emission line that makes that one filter very bright. And that turned out to be the case.

Box 4.1 Glossary of terms (in order of appearance in the transcript)

I	I band (around 0.81 micrometer)
J	J band (around 1.25 micrometer)
H	H band (around 1.65 micrometer)
Balmer break	A feature in the spectra of galaxies that provides clues to the age and history of their stellar population
SED	Spectral Energy Distribution
SED fit	Fit of a galaxy model spectrum to flux measurements in various spectral bands, used to estimate the redshift and physical parameters of the galaxy
Photometric catalog	Table of photometric measurements of galaxies detected in the survey area

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By querying the new CANDELS catalog, van der Wel thus found forty or so objects with I – J colors characteristic of old massive galaxies at redshift 2, but these objects had J – H colors unlike those galaxies. Their J band fluxes were unexpectedly high. This prompted van der Wel to inspect where in the processed photographs these objects are. If all these objects were near bright stars or at the edge of the field – notorious sources of image artifacts –, their photometry and colors would be questionable. But this is not what van der Wel found. Instead, he saw objects that appeared fainter and smaller than the massive galaxies for which he had searched.

Six years after this episode, van der Wel did not recall when he first used diagrams to make sense of these anomalous objects. He told me that "often I was just playing around by hand first … and I haven't saved that." But when he browsed through the computer scripts pertaining to this project, he noticed that "those color-color plots … they appear very early." He had prepared them for various combinations of colors as he explored these anomalous objects' properties.

After accepting that these curious objects were not artifactual, van der Wel gathered the CANDELS team's expertise and found additional data to compose a manuscript describing this discovery. At a CANDELS teleconference in July 2011, at which about fifteen team members were present, Arjen van der Wel presented an advanced draft. He opens the meeting with reviewing it. Figure 4.5 depicts the diagrams to which he refers. A glossary of key terms follows the transcript (see Box 4.2).

Transcript 4.8

I guess I'll talk for two minutes through the figures … basically. What's happening is here is that we have noticed weird objects in color-color space. In ((*Figure 4.5a*)) you see outliers in I – J versus J – H … ehm … just things with weird colors … and if you look at ((*Figure 4.5b*)) I show SEDs of those that are in ERS ((*Early Release Science*)) territory and have all similar SEDs … very flat in F(ν) … so $\beta = -2$ in F(λ) … and they stick out in the J band. After thinking about that for a while we concluded that these must be bright emission lines that contribute pretty much the same amount of light in the J band as in the ((*spectral*)) continuum … implying very large equivalent widths … about 1000 ((*Ångstrom*)) or 1500 ((*Ångstrom*)) in the observed frame. That's quite crazy … ehm … so we checked what if a few of those objects might overlap with existing grism ((*spectra*)) data … so Amber ((*Straughn*)) and Ben ((*Weiner*)) looked at that and that's what's shown in ((*Figure 4.5c*)). Among the 52 candidates that I talk about in the current draft there are four that fall within grism exposures and all four are [OIII] emitters. You can see it's [OIII] because of the asymmetry of the [OIII] line … it has two components … that's

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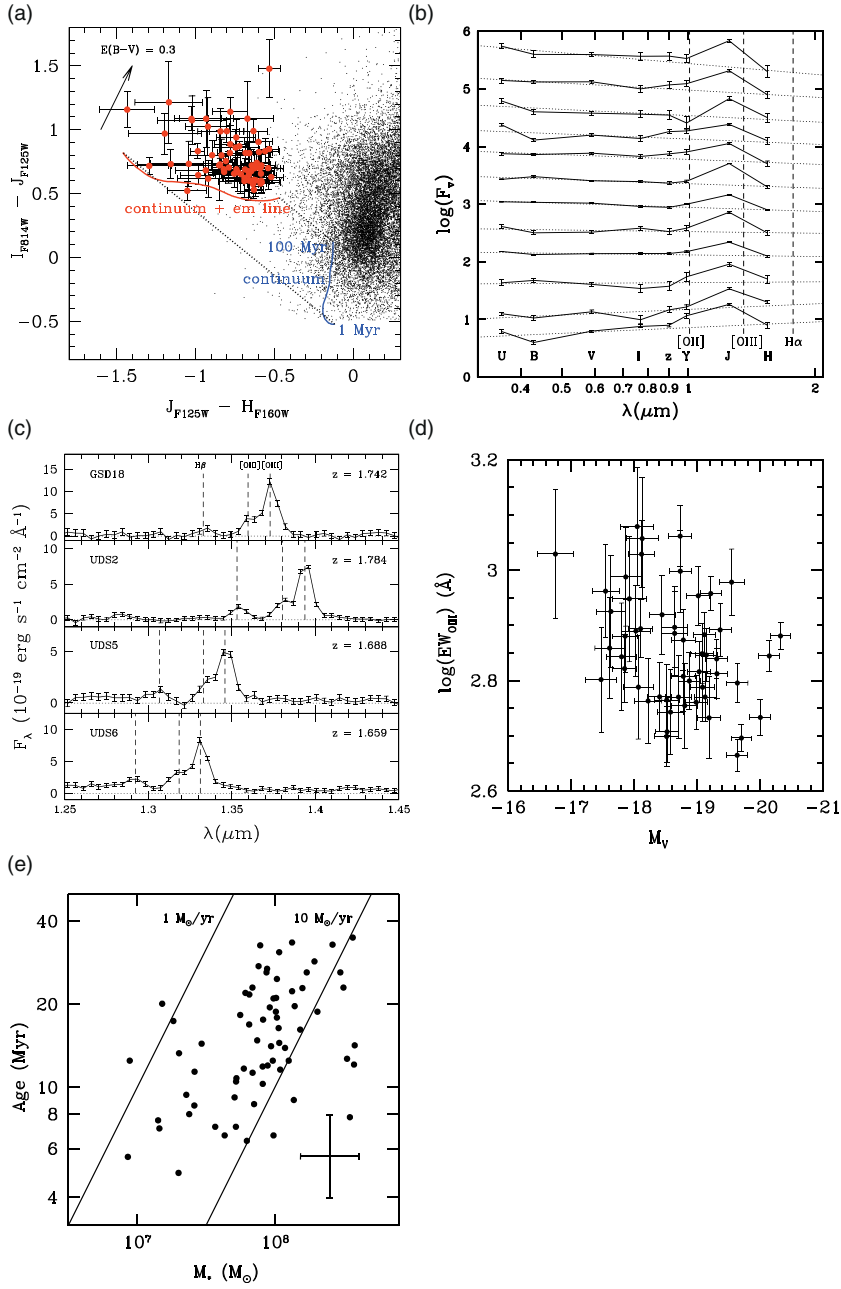


Figure 4.5 Figures of Arjen van der Wel's manuscript as discussed in the text. Figure captions omitted. (© American Astronomical Society. Reproduced with permission.)
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4959 ((*Ångstrom*)) and 5007 ((*Ångstrom*)) … and then in most cases there is a clear indication of Hβ.

So … ehm … this is perfectly consistent with what you would derive from just the photometry. [OIII] in the J band would usually put Hα in the H band unless the thing is at redshift higher than 1.6 and boost the Hα beyond the H band. You can read more details in the paper … of course … but the photometry suggests that it's [OIII]. So that's the premise … for all these objects that [OIII] is dominating this J band excess light.

So then … from the photometry alone … I derive the luminosities and equivalent widths of the [OIII] line … the V band continuum luminosity … just to show what these objects … what their distribution is … I show that in ((*Figure 4.5d*)) … this is also given in the table. And these are the basic properties that I use together with the Starburst99 model to say what these objects are. And what these objects are is shown in ((*Figure 4.5e*)). So they're typically 10^8 solar mass … 10 to 50 million year old … so very young … starbursts … Now all the light you see is from the starburst and it is hard to really constrain the amount of older stars. These things are certainly less than 10^9 solar masses if you look at the IRAC photometry … that's the best constraint you get.

So that's the basic properties of these things … and we put this in a narrative that's more or less as follows … The idea is that the stellar populations of present-day dwarf galaxies formed in a series of bursts at some redshift … and we pitch this discovery as evidence for that. Strong bursts of star formation at redshift 1.7 that basically correspond to the stellar populations that we see today in old dwarf galaxies.

Box 4.2 Glossary of terms (in order of appearance in the transcript)

F(ν)	Flux density of the spectral continuum as a function of the frequency of light
F(λ)	Flux density of the spectral continuum as a function of the wavelength of light
β	Exponent of the power law approximation of a spectral continuum
Grism	A grating prism that combines imaging and spectroscopy; the WFC3 camera on the HST has a grism mode that was used for this study
Equivalent width	Measure of the broadening of lines in galaxy spectra. Large equivalent widths indicate intense star formation
[OIII]	"Forbidden" twice ionized emission line of oxygen, at rest wavelengths 4959 and 5007 Ångstrom, a tracer of star formation in galaxies
Hβ	Hydrogen emission line, a tracer of star formation in galaxies

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Hα	Hydrogen emission line, a tracer of star formation in galaxies
Starburst99	Computer model widely used to estimate star formation histories from observed spectra (Leitherer et al. 1999)
IRAC	Infrared Array Camera on board the NASA spacecraft Spitzer for measuring mid-infrared radiation
starburst	Period of intense star formation in a galaxy

Presenting the draft as a commentary on its figures, van der Wel does not mention his initial concern with image artifacts. Instead, he begins his report with noticing these "weird objects in color-color space." Represented as red dots with error bars in Figure 4.5a, their distance in the scatterplot from "normal" galaxies – visible as a "cloud" of black points – appears to be a measure of their "weirdness."

Van der Wel attributes this offset to the brighter-than-expected J band fluxes in these objects' SEDs (Figure 4.5b). He and his colleagues next suspect that the excess flux is due to a single emission line in the J band which adds to the light emitted by the galaxies' spectral continuum. To add the flux required to produce the excess J band light, such lines would need to be so bright and broad that van der Wel calls them "crazy," and this explanation "outlandish" (Transcript 4.7). However, so-called grism spectra are available for four of these objects (Figure 4.5c),[18] and these show that at least for them the excessive J band flux is indeed due to bright and broad emission lines characteristic of intense star formation events (starbursts). Surmising that this applies to all fifty-two anomalous objects in the sample, van der Wel plots the emission line widths versus the galaxies' luminosities, after using a cosmological standard model to infer distances from estimated redshifts (Figure 4.5d). Plugging the measured values into a model that simulates spectra of star bursting galaxies (Starburst99; Leitherer et al. 1999) yields absolute physical parameters and shows "what these objects are" (Figure 4.5e).

Van der Wel's draft did not include images of these galaxies, but only the diagrams shown in Figure 4.5. At the end of the teleconference, when edits to the draft were discussed, one participant remarked: "I'd think like we'd all like to see pictures of the galaxies … at least." Van der Wel responded: "They're little dots," prompting chuckling among participants and arguably

[18] Grisms are elements in a camera combining a grating with a prism to record spectra of sources in a photograph. The WFC3 camera on the HST is equipped with a grism.

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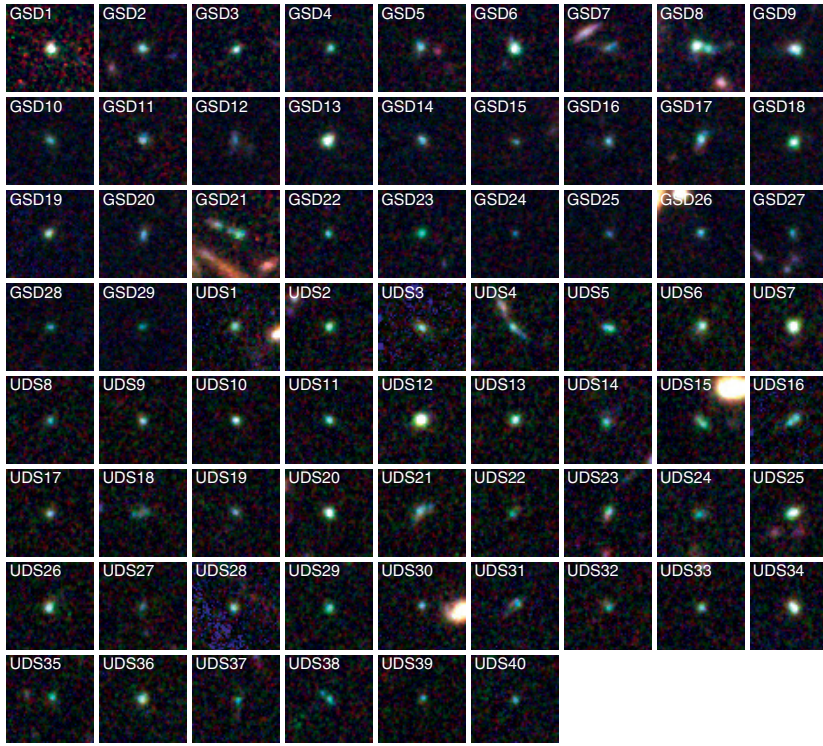


Figure 4.6 False color images of the galaxies in van der Wel's sample, made using Hubble Space Telescope I, J, and H exposures. This is Figure 2 of the published article (van der Wel et al. 2011), inserted between Figures 1 and 2 (Figures 4.5a and 4.5b) of the draft discussed in the text. Most galaxies seem to be compact, but some appear to be extended or have multiple components. (© American Astronomical Society/NASA/ESA/ Hubble Space Telescope. Reproduced with permission.)
Note: The online version shows the colors of the original figure.

implying that these objects look inconspicuous. But, subsequently, he and his coauthors agreed to include a panel of images of the sample's (by then) sixty-nine galaxies in the publication, cut out from the survey images (Figure 4.6).

Thus, it turned out that the "jump" between the I and J bands in these objects' SEDs does not indicate the Balmer break characteristic of old massive galaxies at redshift 2, but is due to bursts of star formation causing an emission line in low-mass dwarf galaxies at redshifts around 1.7. This is a serendipitous, data-driven discovery. Van der Wel's account turns surprisingly "weird" objects into reasonable ones by successively demonstrating that an unusual spectral feature is physically meaningful in an interpretation that

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locates these objects in a communally accepted narrative of galaxy evolution. Known to van der Wel and other CANDELS members, many nearby (low redshift) dwarf galaxies contain populations of what are now old stars that may well have formed at redshifts around 1.7.[19]

Note how this move from color differences to absolute physical properties is a move toward higher externality and greater evidential specificity (Pinch 1985; cf. Chapter 3). Only at high externality is the discourse on galaxy evolution liberated from specific observational detail, such that the Balmer break of redshift 2 galaxies is between the I and J bands. Thanks to this narrativization, these objects are no longer a conundrum to van der Wel and his colleagues. Instead, they confirm and strengthen an existing scenario of low-mass galaxy evolution.[20] Neither image artifacts nor questions of survey completeness (as in Peter's critique earlier) challenge this discovery and van der Wel and his coauthors introduce a name (Extreme Emission-Line Galaxies) and acronym (EELGs) for these objects that have been adopted in the literature since. But the strength of this narrative arguably is its tie with the diagrams. As Arjen van der Wel insists: "Diagrams are the most important things. I always make the figures first. If they don't show a story … there is no story."

4.5 Playing with Data

Both Peter and Arjen van der Wel emphasize the importance of play in their work with data, and for both play is tied to using diagrams. Peter responds to Nadine's histogram, made late in her project, and suggests play to avoid incompleteness issues that may invalidate an interpretation. The play that Peter proposes is systematic: moving from bin to bin across the scatterplot (Figure 4.3) and assessing how their inclusion affects the $n(z)$ histogram's shape. Arjen van der Wel's play is more exploratory, as he constructs various color-color plots, hoping to get a better sense of anomalous objects. Peter and Arjen van der Wel both use play as they face

[19] Van der Wel et al. (2011). EELGs have been identified at redshifts from 0.2 (in the nearby universe, where they seem to be identical with the so-called Green Pea galaxies; Cardamone et al. 2009) to 9 (in the distant, early universe; Llerena et al. 2024).

[20] Note van der Wel's repeated use of the discourse marker "so" in Transcripts 4.7 and 4.8, which may mark the continuation of his storytelling, indicate preliminary conclusions, and initiate incipient consequential next actions which typically refer to diagrams and include, in line 1 of Transcript 4.7, graphical gestures. In Transcripts 4.2 to 4.6, Peter uses "so" similarly. See Bolden (2009) on various uses of "so," as well as Netz (1999) and de Freitas (2012) for links of (mathematical) diagrams with narrative structures.

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uncertainty: "What is still acceptable?" (Peter). "What does this mean?" (van der Wel).

Play is an essential part of scientists' practical methodology. In their play, Peter and Arjen van der Wel do not pursue joy aimlessly or participate in a game that is inconsequential for life beyond its boundaries – aspects of play that philosophers have mostly pondered.[21] They rather explore possible alternative actions for deciding which among them to adopt and make consequential. Their play is set apart from ordinary, sequential courses of action by a metacommunicative frame (indicating that "this is play"; Bateson 1972), involving actions that are often deemed reversible (Huizinga 1955). By acknowledging that there are several alternatives of which one may be favored, play is an "intellectual insurance policy" (Nguyen 2022, 269).[22] Both Peter and Arjen van der Wel examine what they can get away with, that is, what other scientists will accept – presuming, conversely, that this is what they themselves find acceptable in others' work.

Play is tied to diagrams because diagrams make different alternatives visible and comparable. In data-rich science, they provide a sort of playground for exploratory work. Always done with somebody or something, and bounded spatially or by rules, play is often marked by movement in relation to a visual structure such as a field, board, or diagram. Thus, as psychologist F. J. J. Buytendijk observed, "the domain of play is the domain of the image" (1933, 129; my translation). How play will unfold is not knowable in advance. To play means to relinquish one's control: "one does not only play but is being played with" (Buytendijk 1933, 117). Employed when facing uncertainty, the outcome of play is not predictable. Surprises must be possible.[23]

Scientists play with data of various externalities and evidential specificities (Pinch 1985). This play includes early stages of data analysis. Consider

[21] Huizinga (1955), Suits (1978), Fink (2016), and Nguyen (2020).

[22] This resembles the "dirt gate" that Mody (2001, 26) observed in the work of materials scientists, where dirt in samples "seems to be an 'even though' gate; if the desired finding appears 'even though' dirt is present, then the finding will be more durable and, for practical reasons, more valuable." In astronomers' uses of machine learning, adversarial attacks play a similar role of introducing variations into data and models that allow assessing the robustness of interpretations (Huang et al. 2022).

[23] There is a resemblance of "playing with data" with "exploratory experimentation" (Steinle 1997; Franklin 2005) and "tinkering" (Lévi-Strauss 1966; Jacob 1977; Knorr Cetina 1981), but accounts of the latter two typically neglect uses of diagrams and visualizations, whereas descriptions of laboratory experimentation as "games" (Jacob 1982; Rheinberger 1997) and of board games as an analogy for scientific practice (Latour and Woolgar 1986, ch. 6; Sormani 2015) do not. Tukey and Wilk (1966, 696–697) already noticed that "data analysis is like doing experiments" and emphasized the role of visualization therein (see also Hullman and Gelman 2021).

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the work of Patrick, a postdoctoral scholar in Otfried's group. Whereas Nadine worked on the A2713 dataset, Patrick was to analyze the MAMBO dataset of another galaxy cluster, A2714. New to the template-fitting technique and to data from the Omega near-infrared camera, Patrick was troubled that the slowness of his computer restricted his ability to "play" with the parameter settings in the data-reduction pipeline:

Transcript 4.9

1 Patrick: It took forever … you could not explore the parameter space in the reductions … for if every step takes several hours you have to think in advance if ((*the settings are*)) okay … and you cannot play around much. At first it took me some time … because I always made a mistake somewhere. I wasn't familiar with it … and so you play with it a bit more. And then … when you've played it through five times or so … and you understand the dataset … then it is … then you do the final data reduction and that's it.

2 Götz: Playing with what? The parameters?

3 Patrick: Well … I used to work with spectra and there are diverse possibilities. Here it is like that as well … and you wonder: Should I do another superflat correction? Should I subtract the background? How does it look like? Do I improve things? (…) You can think about much of this in advance … but in the end you want to see how it looks like.

His computer's apparent slowness invites Patrick to reason about what may be unremarkable otherwise: suspending sequential work for a period of play oriented toward deciding which action among potential alternatives to choose and make consequential for subsequent work. He is aware of the choices available to him in terms of procedures and the "parameter space," and he argues that it was through his play that he could properly "understand" the set of digital exposures constituting his data. Doing so involves assessments of previous actions. Patrick's mode of play is more interactive and faster paced than the play that Peter and Arjen van der Wel describe. But just like them, Patrick constructs alternatives that he assesses visually. His play is tied to diagrams as well, if we recognize digital photographic exposures as such.[24]

[24] Patrick's on-screen play arguably bears a resemblance with single-player video gaming (cf. Sudnow 1983; Reeves et al. 2017). For early remarks on astronomers' play with digital images, see Disney (1979). Note also Derrida's (1978) remarks on freedom and constraint in the play that certain (logical) structures enable (cf. Fortun 2009).

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4.6 Accountable Exposures

So far, we have examined diagrams as resources for intersubjective action, for pruning a dataset, for surveying complex datasets, for making a scientific discovery, and as venues for doing so exploratively and playfully. In this work, diagrams are resources for holding others to account and this commonly happens far beyond face-to-face encounters. This accountability is not restricted to histograms and scatterplots but includes the photographic exposures (like Figure 4.6) on which the measurements they represent are based. It is at the micro-level of pixels that visual assessments meet the rigor and intersubjective force of mathematical notation.[25] Let me illustrate this with how individual exposures can be made accountable to globally accepted phenomena.

Remember that digital photographic exposures are two-dimensional "arrays of numbers" (Lynch 1991a; Chapter 1). Not only can one represent with diagrams how these exposures are processed arithmetically (Figure 4.7). If we adopt philosopher Charles Sanders Peirce's understanding of diagrams as "signs whose parts have analogous relations to those of their objects" (Alač 2011, 41), then we can recognize that many astronomers take digital pixel exposures to be diagrammatic in this sense.[26] Thus, a common way to make a completeness map for examining the limit sensitivity of a photographic galaxy survey – something that Peter wants, but cannot easily have, for Nadine's sample (Transcript 4.6, line 226) – is to randomly insert artificial digital galaxy images of various shapes, sizes, and magnitudes into a wide-field pixel image and examine which fraction of these an object detection code retrieves. This wide-field image is then treated like an image of the sky in which only natural objects are detected.[27]

[25] See Chapter 1 and compare Rotman (2000, 58), who insists that "without rigor, mathematics would vanish," since "rigor is not an externally enforced program of foundational hygiene, but rather an intrinsic and inescapable demand proceeding from writing." It is basic to transforming "mathematical intuition into an intersubjective writing/thinking practice." On visual evidence as a resource for accounting practices, see Neyland and Coopmans (2014).

[26] Peirce's notion of iconic signs is not exhausted by (photographic) images, which resemble their objects by looking like them. He also considered diagrams and metaphors as icons, the former because of resembling their objects in the analogous making-up of their parts, the latter because of other kinds of "parallelism" (Peirce 1931–1958 (1934), vol. 2, §277). Thus understood, iconicity reaches beyond what can be seen. Conceived as iconic signs, photographic exposures may likewise be regarded as diagrams which promise new insights into their objects by revealing otherwise hidden analogies when being experimented upon (Peirce 1933, vol. 4, §530–531).

[27] Among many others, Giavalisco et al. (2004, L97–L98) employ this technique without referencing it, which suggests that it is not in need of being explained to members. See Hoeppe (2020b) for an examination of its use in contesting a discovery claim. Each pixel in a calibrated digital photograph is a measurement; an image is an array of measurements.

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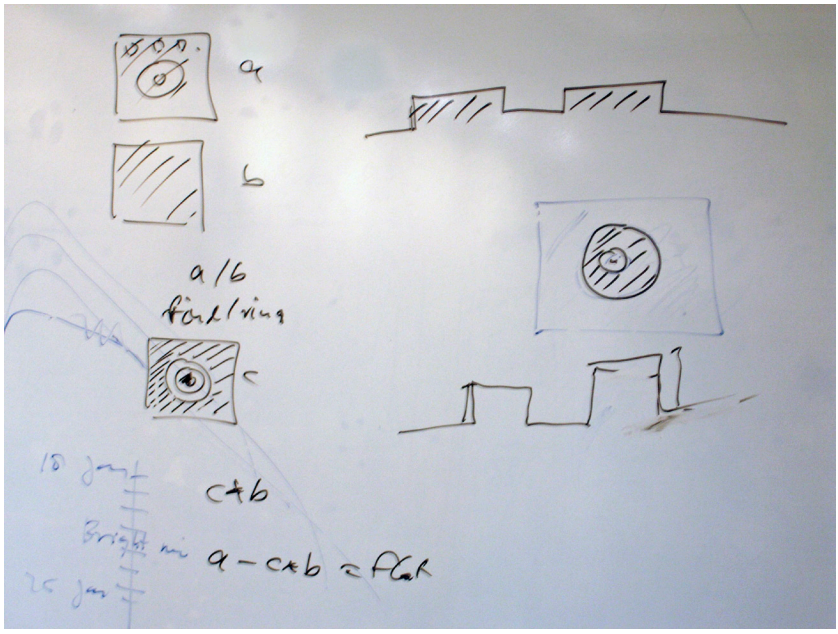


Figure 4.7 Otto's sketch of the sequence of arithmetic operations (left) that Nadine was to apply to remedy her flatfield issue. The outlines of a flatfield exposure (a), a noise pattern (b), and the modeled ring (c) are drawn schematically as square outlines of the infrared camera's 2048 pixels × 2048 pixels. The sketches at the right top and bottom represent cross-sections of the intensity of scattered light across the flatfield. An arithmetic formula describes how scattered light is to be removed. See also Figure 3.6. (Photograph: Götz Hoeppe)
Note: The online version shows the colors of the original figure.

Elsewhere I present episodes from the work of the MAMBO team to examine how stabilized, agreed-upon phenomena of astronomical discourse (such as the shapes of stellar and galaxy spectra) can serve as resources for the calibration of photographic exposures (Hoeppe 2019b). One of these episodes describes how Nadine removed the ring-like feature in her flatfield exposures that Otfried and his colleagues considered to be artifactual (cf. Chapters 3 and 5). These scientists oriented to flatfield calibration frames and science exposures in distinct ways. Taken during twilight before stars appear in the sky and lacking as such a referent external to the observing situation, flatfield exposures were not made accountable as images of celestial objects but were held to index a telescope and camera's optical performance only. Intended to help remedying local artifacts, flatfields were manipulated in a pixel-by-pixel way, sometimes by hand,

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conditional upon their further computational use. In this prospective and retrospective work, calibration frames were recursively adjusted. They were made visually and numerically accountable to artifacts of the local observing situation.

By contrast, team members never manipulated individual pixels in science exposures. Understanding them as indexing cosmic objects, they used science exposures as entire frames throughout. As such, they considered these exposures as "computationally distinct" from calibration frames.[28] They made science images (the science exposures as divided by the flatfield) numerically accountable, through measurements of their pixel values, to template galaxy SEDs (a sort of model) on which communal agreement, reaching beyond this group and involving different evidential contexts, had been achieved before. Thus understood, they shaped these science images as a medium that reproduces stabilized forms of extragalactic astronomy, while retaining the capacity to surprise researchers.[29]

In another episode, I witnessed how Patrick, the postdoctoral scholar quoted in Transcript 4.9, responded to a challenge in his work on the team's exposures of the galaxy cluster A2714. A known issue with straylight in the camera, much as in Nadine's case, was complicated by the fact that several changes to the telescope's mechanical structure had been made over the four years in which the exposures of A2714 were recorded. Upon closer inspection of the exposures taken at different epochs, Patrick and his supervisor Otfried noticed that stars in the image's corners did not look round (as desired) but appeared to be more and more distorted the further they were away from the image's center. This effect appeared to grow worse over time. Otfried interpreted it as an optical error (astigmatism) caused by changes in the telescope's mechanical structure.

In discussion with Otfried, Patrick first considered using only the inner parts of exposures, where the distortions were small. However, since the cluster galaxies were distributed across the entire field, this would have curtailed the sample size in ways unacceptable for their project. The team's data-reduction software did not allow for consistently correcting artifacts whose shape varied across the images. Patrick next considered abandoning treating his exposures as a unit, but splitting them into a grid of 4 × 4 subfields and correcting the image distortions separately in each subfield.

[28] In flatfield division, science exposures are the dividend and flatfields the divisor, a divisor that is a unitless number (the relative sensitivity of pixels).

[29] In Hoeppe (2019b), I argue that Luhmann's (2012) distinction of medium and form can be brought into a domain of social accountability for describing how the replication of astronomical phenomena reflexively shapes the formatting of digital images as data suited for reuse.

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He would then work with sets of sixteen exposures instead of single ones. Although technically feasible, doing so would have dramatically increased the number of choices for which they would have to account. This would have weakened whatever conclusion they could draw from these data. Troubled by this prospect, Otfried decided that Patrick should abandon work on this dataset.

Thus, salvaging the exposures of A2714 would have risked making the data "too soft" for discovery work, because scientists' capacity to attribute distinctions in them to epistemic novelty was compromised. The point is not that the computations involved could not possibly be made to match existing work and claim a discovery, but that only a certain effort to do so seemed legitimate to these researchers. This is a social accountability.

4.7 Discussion: Locality and Distance in Data-Rich Science

I conclude this chapter by pointing out some of these episodes' implications for claims made in science and technology studies about the localness of scientific work. Empirical studies of scientific practice by historians and ethnographers of science have emphasized the local origins of scientific knowledge in laboratories, observatories, and field sites.[30] Some of these studies have examined how such findings travel elsewhere, often only with considerable effort, through arranging public demonstrations and building infrastructure, as well as developing and enforcing calibrations and standards.[31] Leonelli's (2016, 69) notion of "data journeys" takes this image up and makes it productive as one way to consider data as "tools for communication."[32]

Historian Mario Biagioli (2006) takes issue with the "localist thrust" that he blames mostly on the sociology of scientific knowledge. Biagioli observes that the focus on the local has led to ascribing to distance a "central but negative role in recent interpretive models in science studies and the history of science" (Biagioli 2006, 22). It is exemplified, he claims, by Harry Collins' (1992, 145) notion that "[d]istance lends enchantment: the more distant in social space or time is the locus of creation of knowledge the more certain it is." Biagioli challenges negative assessments of distance with his study of Galileo Galilei, whom he portrays as a strategic actor

[30] See Garfinkel et al. (1981), and Shapin and Schaffer (1985), as well as Henke and Gieryn (2008).
[31] See, for example, Latour (1987) and Galison (2008).
[32] See also Leonelli and Tempini (2020). Borgman and Groth (2025) examine diverse kinds of "distance" in the reuse of scientific data.

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who withheld data and delayed sharing it to increase his own authority and aura. Biagioli contends that this demonstrates the productive use of distance in the making not only of authority: "Once we consider the productive roles of distance, knowledge appears as something that is never completely local, not even at its so-called moment of origin" (Biagioli 2006, 74).

When we attend to the social accountabilities involved in data uses, the episodes discussed in this chapter add substance to Biagioli's claim. They show how scientists were oriented throughout toward other researchers and mindful that these would evaluate and assess their work. This was perhaps most clear with Peter's concern about Nadine's histogram, which can be read as a concern about the team's reputation (Transcript 4.3, line 61). But it also mattered to Arjen van der Wel's study, as well as to how Otfried guided Nadine and Patrick to use digital photographic exposures as "workable objects" whose usefulness was not guaranteed initially. Local work was oriented to potential reuses of images (as processed exposures) by researchers elsewhere, as demonstrated by concerns with the integrity of images and with ensuring that, with reasonable effort, their work can be described to others. These scientists display an awareness of being caught in a "web of inferences" regarding their actions (Levinson 1983, 321). Thereby, the distant was always present in work that was ostensibly local.[33]

[33] By focusing on "local production," ethnomethodology may appear to confine itself to spatially delimited face-to-face settings. However, as Lynch (1993, 125) insists, it is better understood as describing the production and reproduction of orderliness without "theoretically postulating a homogenous domain" like "panlinguistic structures, cognitive structures, *doxa*, or historical discourses." As described in Chapter 3, astronomers do use globally established phenomena and cosmological models as resources for the orderly production of data. But in many cases, the "production cohort" (Livingston 1987) of reusable digital images includes their possible future users, whose reciprocal perspective on their work data makers anticipate (see Chapter 8). For an extended meditation on the locality of data, see Loukissas (2019). See also Wittgenstein (1978), Warwick (1995), and Rotman (2000) on social accountabilities of notation and computation.

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