ISSN 1744-1986

Technical Report N° 2009/ 12

Representations for Idea Capture in Early Software and Hardware Development

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18 January, 2009

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Abstract

This paper presents evidence of how professional software and hardware designers currently capture ideas early in the design process, both individually and in collaboration. The paper reports in detail on a corpus study of over 1000 examples of idea capture representations collected from 15 designers in various design teams over 6 years. Examples include informal notes and sketches which designers made for their personal use, as well as sketches made for discussion at meetings, on whiteboards, in the pub, etc. The paper characterises the corpus, discussing which representations designers use when allowed to choose freely, how designers' informal representations relate to the formal representations from their discipline, how the character of their informal representations facilitates design discussions, and why many of the functions afforded by their sketching are not well supported by existing CAD systems. It discusses what the observations and sketches reveal about requirements for an idea-capture tool that supports collaborative design.

1. Introduction: idea capture in early design

Conceptual-level reasoning is reflected in the sketches and other informal representations experts make when exploring early design ideas. Notes and sketches allow designers to capture ideas early in the conceptual design process when the ideas are perhaps incomplete and fleeting – these informal representations have a role in capturing, generating, and evaluating design ideas. Lansdowne [11] writes that "…sketching is needed not simply to illustrate completed ideas to others…its main purpose is to assist designers in eliciting, developing and evaluating the design ideas themselves." (p. 1) He reports that good designers are better at externalizing ideas than less able ones, and that they do it earlier in the design process.

1.1. Sketching as an 'intelligence amplifier'

Cross [3] calls sketching an "intelligence amplifier" and enumerates how sketching helps design thinking: enabling designers to handle different levels of abstraction simultaneously, enabling identification and recall of relevant knowledge, assisting problem structuring through solution attempts, promoting recognition of emergent features and properties (pp. 34-38). Other researchers, too, write about the role of external representations in assisting creativity and cognition. Goldschmidt [7] describes the 'dialectic of sketching': that design is a dialog between the designer and the sketch, in which the externalization plays a key role in cognition, reflection, and creativity. Sketches allow a dialectic between perception of the figural properties in a sketch ('seeing as') and non-figural propositions about the design ('seeing that'), hence "…allows the translation of the particulars of form into generic qualities and generic rules into specific appearances" (p. 139). Schön [19], too observes the reflective dialog with materials, the externalization of design "talking back" to the designer and providing insight.

The imprecision, ambiguity and generality of manipulation of free-hand representations is considered by many to be crucial to design creativity. Goel [6] presents evidence that free-hand sketching "by virtue of being 'dense' and ambiguous – correlates with creative, explorative, ill-structured phases of problem solving and the avoidance of early fixation. Fish and Scrivener [5] argued that creativity is supported by the sorts of selective or fragmentary information and indeterminacies typical of sketches; the abstraction and indeterminacies help in preserving or suggesting alternatives.

1.2. Sketching in conceptual design

A variety of researchers have investigated the role of sketching in early design in various domains, for example: McGown et al. [15] - mechanical engineering and architecture; Schenk [18] - graphic design, Hewson [9] - typographic design; Suwa and Tversky [21] architectural design. These researchers have argued that the conceptual stages of design are not adequately supported by computer-based tools, and that an understanding of the roles and conduct of sketching should underpin tool development. Jenkins and Martin [10], focusing on the conceptual design stage, provided an analysis of the differences between free-hand sketching and the facilities provided by CAD packages.

There is little theory about how either the sketching process or graphical representations actually assists cognition. Simon [20] recognizes designers' needs to externalize their thoughts and discusses the ways this can aid mental processes. Purcel and Gero [16], in their review of research into sketching and its role in design, concluded that the literature on sketching is largely descriptive. They identified theoretically-developed areas in cognitive psychology which can be used to develop theory about sketching in design. Similarly, Scaife and Rogers [1996] considered the lack of theory regarding the effectiveness of graphical representations and promoted an alternative approach that analyses how different graphical representations work in terms of core ‘‘external cognition’’ processes and properties of the graphical representation, such as computational off-loading, re-representation and graphical constraining. Larkin and Simon [12] offered one theoretical account of graphical representations, encompassing the properties of the graphical representation, the way that these properties may be represented internally, and computational processes that mediate between the two.

1.3. Sketching in collaboration

Conceptual design in hardware/software design is often collaborative. Developers work in face-to-face settings, creating many sketches on paper [1] or on whiteboards [4]. Not only must designers think about design, but they must also communicate their concepts and coordinate their thinking across the team in order to develop a shared vision. In this context, sketches can not only capture early ideas, but also potentially communicate them and act as a coordination mechanism to support the design dialogue. Lubars, Potts and Richter [13] conducted a study of the requirements analysis process in 23 organizations, which demonstrated clearly that informal documentation, communication and coordination are all more important during what we now call the conceptual design phase, than conventional notational and analytic methodologies. Luff et al [14], based on field studies of real-world organizational environments, concluded that paper-based representations had particular advantages for collaboration. The ‘tailorability’ of paper-based documentation (e.g., its amenability to annotation) and its ‘ecological flexibility’ (its ability to move around the environment) were key features.

1.4. Idea capture representations in software and computer system design

The study reported in this paper follows in this tradition, with a focus on computer software and hardware design. What representations do software and hardware designers use during conceptual design when they are free to choose (i.e., given pencil and the back of an envelope)? In order to find out, we examined the informal notes software and hardware designers make during the earliest design phases. The corpus analysis was supported by concurrent observations that allowed a consideration of the behaviors associated with the generation and use of the collected corpus.

Section 2 describes the background and conduct of the study. Section 3 reports the corpus analysis and the categories that emerged. Section 4 reports patterns of representation observed across the corpus. Section 5 draws on observations conducted during the collection of the corpus to relate the collected representations to observed designer behaviours. It also includes observations about CAD system usage by the contributing designers. Section 6 reiterates the key findings.

2. Background and data collection

A number of designers on development teams for various projects in three companies were observed and interviewed as part of ongoing research over six years. Our research during that period concerned various aspects of innovation and design, including: reasoning and problem solving, team communication and collaboration, and use of representations and tools. Our research in the companies included periods of intensive observation, in some cases a week at a time, in one case a day per week over more than a year. During this intensive observation, we observed both individual and group working, including meetings, informal interactions, debugging sessions, and so on – we followed design activity where ever it focused.

2.1. Companies

The 3 companies were all commercially successful. Their profiles were characterised by the generation of intellectual property and the anticipation of new markets. The companies were small, not more than 200-300 employees, although 2 were autonomous subsidiaries of much larger companies. The companies were fluid in their constitution of teams, often engaging designers in more than one project team (depending on the size of the project) and gradually altering the constituency of teams over time. The managment saw this as benefiting knowledge transfer within the company and keeping the team dynamics fresh.

2.2. Teams

The designers were all members of small teams of 3 to 12 members, all included at least one expert programmer of the calibre of ‘super designer’ [2]. All were high-performance teams: effective intellectual-property-producing teams that tend to produce appropriate products on time, on budget, and running first time. The constitution of the teams varied with the projects: some were software teams, some were involved in hardware/software co-design, some were multi-disciplinary, concurrent engineering teams involving hardware and software design, with elements of mechanical and cosmetics design, and with input from marketing and production throughout the design process. The projects we observed all required substantial software design, often with a balance between hardware and software design. Some were software-led, although some were electronics-led,: consumer electronics, electronic instrumentation, embedded processor products, professional audio, video and broadcast equipment, computer systems, and so on. The teams were generating new products rather than maintaining or extended existing ones. Each of the teams was user-oriented and brought user input into the design process from the earliest stages, although they did not typically engage in fully participatory, user-centered design.

2.3. Documents

From 15 of the designers, in the course of observations undertaken over 6 years, we collected 'idea capture' documents, e.g., informal notes and sketches for personal and discussion purposes made at meetings, on whiteboards, at the coffee machine, in the pub, etc. during the early stages of design. The documents covered a number of projects from a number of teams for each designer. It included all relevant material generated on the days which we spent observing in the companies, as well as additional material collected by the designers in our absence. It included 'ephemera' (i.e., material the designers themselves disposed of quickly) as well as documents they kept in their own records. The collection amassed available material and was neither selective nor comprehensive. However, we consider the corpus to be representative of idea capture documents in the contexts studied, as did the designers who supplied the material.

The corpus includes 1055 sheets (or equivalent, as in single images of whiteboards). Most are A4; a few are smaller, and a few are larger. Most sketches started on blank sheets (or blank whiteboards), but some were added to printouts or were made on the reverse side of other material.

3. Analysis and categorization of representations

The corpus was analysed in order to discover what representations designers use for their most informal and personal capture of early design ideas. The documents were all categorized independently by two expert designers (one hardware and one software expert, both used to working on multi-disciplinary teams) in terms of the representations contained.

18 categories were identified, as follows:

1. A algebra
2. B bus (physical schematic)
3. C curve (plot of a function)
4. D design for a physical object or display
5. E executable (i.e., source code, pseudo-code)
6. F frequency response
7. G geometric drawing
8. H hierarchical structure diagram
9. L list (alpha-numeric)
10. M map (e.g., plot of points in space)
11. N numeric (e.g., values, calculations, numeric tables – other than algebra)
12. P pole/zero plot
13. S schematic
14. SS scenario sketch
15. T timing diagram
16. W waveform
17. X doodle
18. Z natural language (e.g., written notes, draft communications)

Examples are shown in Figures 1-6.

The experts produced nearly identical categorizations, with only minor differences in naming and occasional omissions. And any discrepancies were resolved by consultation with the experts, so that each was satisfied with the final categorisation.

The number and proportion of examples of any given category are not reported here, because those metrics are not meaningful in this context: the use and distribution of representations changes depending on the task and on the role of the designer in the project (e.g., hardware designers on a given team working on a signal processing project produced more *bus* sketches, whereas software designers produced more *executable* fragments). Some categories, such as scenario sketches, appeared less frequently, but their very existence was informative. Therefore, the analysis reported here focuses on patterns indicated across the whole corpus which were consistent with observed and reported usage. It is considered that counts or percentages would be ungeneraliseable and therefore misleading.

4. Patterns of representation

Only 18 categories of representation were identified across the whole corpus. Although individual categories and therefore the particular number of categories might be considered a matter of interpretation, it is notable that, even when given free choice of representations, designers use a limited number of different representations. All teams used at least 12 of the representations, and most used more. Thus, their repertoire of representations was limited, but also varied. Individual use of representations was more variable.

4.1. Reference to formal representations

As indicated in Table 1, many of these sketched representations (10 of 18) referred to formal representations in the design disciplines (e.g., *schematic*, *wave form*, *executable*). Each designer and each team used variants of formal representations as well as informal representations. Often, these 'formal' variants were interpreted more freely than they might be 'downstream' in the design process.

This freedom of expression took the form of using what was directly relevant and useful from the formal representation, disregarding elements that were not, and possibly adding additional elements. Designers might produce incomplete fragments, disregard syntax rules (even commenting that "this wouldn't work like this…", include 'place holder' elements or elements that were not formally part of the notation or component library, add in elements from a different representation, represent alternatives, annotate freely, and so on. Exploiting this freedom allowed the designers to express things that were not addressed or were excluded by the formal representation.

4.2. Generic representations

Other representations were generic (e.g., *list*), extremely versatile (e.g., *numeric*), or both. Some, such as *design for a physical object or display* and *geometric drawing* were freehand sketches. Many reflected high-level structure or planning (e.g., *list*, *map*, *structure diagram*).

Generic representations took the form of both sketching and writing. Sketching and writing were often used in combination, not labels on sketches, but also the juxtaposition of different representations (often related conceptually), such as diagrams and lists. Thumbnail sketches were sometimes used as an iconic index to other material. Some form of writing was rarely absent from a sheet.

Surprisingly little of the corpus was free sketching – the majority referred to formal representations. Yet the informants considered free sketching to be crucially important in idea capture.

4.3. Juxtaposition and co-occurrence

Juxtaposition of different representations and annotation were widespread. Annotation was not identified as a separate category *per se*. Simple annotation, such as labelling, was treated as an inherent part of the representation(s) to which it applied. This was true as well for simple graphical annotation such as highlighting, grouping by circling, and relating using arrows or lines – even when the annotation encompassed more than one form of representation. Many drawings included one representation used to elaborate on some aspect of a different representation. Such annotations were treated as an additional, juxtaposed representation (e.g., *numeric*, *list*, *executable*).

Of the 1055 sheets, 295 (28%) contained only one representation, and the remaining 760 sheets (72%) contained two or more representations, typically but not always capturing related information. Different perspectives (i.e., hardware and software) also occurred together on a single sheet (e.g., *bus* and *executable*).

11 of the 18 categories of representation were used alone (see Table 1). The representations which occurred most frequently on their own were *lists* and calculations (*algebra* and *numeric*). Each of the categories of representation was used in combination with other representations on a single page – no representation always appeared alone.

4.4. Mixed levels of abstraction

Juxtaposition of different representations was not the only form of combination on a single sheet. Designers also frequently mixed representations at different levels of abstraction – both within and across particular categories of representation. Examples of this mix of levels were generated by many designers. The ability to juxtapose material from different levels was associated with consideration of design implications and consequences. This is consistent with Cross [3] who cites the ability to handle different levels of abstraction simultaneously as one of the benefits of sketching.

4.5. Provisionality

A feature of the corpus which distinguishes such informal representations from more formal capture (such as CAD drawings) is the explicit indication of 'provisionality', that what is being represented is not fixed, uncertain, not fully specified, not fully defined, undecided or uncommitted – but is subject to reconsideration and/or alteration. Designers used different qualities of line (e.g., light pressure, broken or wavy lines, different colours), annotations (such as question marks or lists of alternatives or other considerations), and juxtaposition of alternatives as ways of conveying provisionality. The expression of provisionality played a role in focusing attention (and diverting attention), considering alternatives (including marking things for later consideration of alternatives), and deferring decisions. It allowed designers to consider 'downstream' decisions before having all 'upstream' issues resolved.

Hewson [9] documented the importance of 'provisionality' in typographic design and noted that qualities of paper-and-pen/pencil such as pressure, thickness and density of lines contribute to conveying that some aspect of design is subject to alteration – a quality that influenced how designers thought about the content. Fish and Scrivener [5] argued that sketching includes "tolerances and indeterminacies in ways that can amplify the artist's ability to perceive or imagine many options" (p. 117). Something similar appears to apply here, with designers using representations of 'provisionality' to assist their design exploration and discussion.

Information such as crossings out (indicating exclusions, corrections) remain visible in the examples and were referred to during observed discussions. Designers made use of such 'litter', of artefacts remaining from previous activity and discussion, to assist them in recalling the design process, history, and rationale.

4.6. Scenario sketches

The designers drew scenarios: use-oriented views of the whole system in context. These showed up most frequently in representations generated during discussions between team members. They demonstrated a recurrent attention to context and user needs during early design.

5. Relating corpus to observed designer behaviours

The corpus was collected in the course of observations undertaken over a substantial period, and so, although the focus of the study reported here was the analysis of the artefacts, we were also able to draw on observed generation and use of some of the artefacts, and hence to relate the material to designer behaviour. This section summarises some of those observations.

5.1. Generation as 'notes to self'

Many of the sheets were generated as 'notes to self', usually in the course of solitary work, but sometimes as private notes during discussions and collaboration. Any of the categories of representation might arise during solitary working. Those most prominent in notes during collaboration were *lists*, calculations (*numeric*), and representations of structures and planning (e.g., *structure diagrams*, *schematics*, *natural language notes* – written notes about planning). In some cases, the 'notes' to self made during collaboration were more elaborated than group material, often containing specific material not addressed in the broader discussion. Such 'notes to self' were made, for example, when the note-maker was thinking through the implications of something raised in discussion for aspects of the design for which the note-maker was responsible. In other cases, the 'notes to self' were more iconic, for example when they were made as a memory prompt.

5.2. Generation during collaborative discussions

It was unusual to see a group (i.e., two or more) designers get together to discuss a design without making some sort of sketches or notes. If they arrived unprepared to do so, they'd improvise, grabbing whatever means were to hand, for example using marker pens on windows.

The designers used juxtaposition and annotation deliberately and expressively. They would make a deliberate change of representation to highlight key points. They explicitly represented design alternatives in juxtaposition. Annotation, both textual (adding detail, notes, emphasis) and graphical (highlighting, relating) was important and was used dynamically to support dialogues. Crossings out (exclusions, corrections) remained visible, were referred to explicitly, and were sometimes annotated specifically.

The groups often represented context – using scenario sketches, hierarchy and structure diagrams – both as scene-setting and in discussion of specific design decisions, alternating between representations of context and representations of specific design elements.

5.3. Facilitating design discussions

The character of the designers' informal representations facilitated design discussions. A number of qualities were instrumental:

- *Fluidity, ease of annotation, ready ability to change representation* – all made it easy to draw attention, to tease out discrepant understandings, and to provide alternative descriptions/explanations (important for team coordination).
- *Scenarios* helped to establish that everyone was 'on the same page', starting from the big picture.
- *Expressive juxtaposition:* It was important that they could juxtapose representations and easily maintain more than one 'view' or alternative at the same time – keeping the discussion open.
- *Escape from formalism:* Every formalism is a simplification, and occasionally one needs to express something excluded by the simplification — to escape from the constraints of the formalism [8]. This was afforded by the ability to vary the representations that related to formal representations, and crucially by the ability to juxtapose freely. Freedom from syntactic and other rules of a formalism also helped with the need to escape from constraints, to 'break the rules' during conceptual design, in order to imagine and innovate. "Don't worry about that now" was a repeated remark.
- *Provisionality:* The freedom to ignore some things, to indicate some with place holders, and to express a lack of decision ("We haven't decided that yet.") supported fluidity in focus and exploration.
- *History:* History and experience featured regularly in design discussions: "We've been there, and we decided against it." The freedom of annotation allowed designers to express elements of design rationale simply, and to take history into account during exploration of alternatives. The annotations allowed those rationales to be re-examined and questioned subsequently.

5.4. Relating informal notes to CAD system usage

These designers are fluently skilled CAD users. As part of these studies, we made an informal examination of how designers use existing CAD systems for early idea capture when they have to, given that CAD systems are based on models, not sketches.

The CAD systems these designers use (e.g., AutoCAD) are sophisticated, with powerful graphical editors, large libraries, and active user groups. Evidently, the designers are able to use these systems with considerable facility and to good effect. However, early idea capture is not fully served by CAD systems, and certain shortcomings are reported across systems, especially:

- *Premature commitment:* forcing the user to make a decision before the proper information is available [8] – CAD systems tend require a level of precision and detail that is often avoided by designers during conceptual design;
- *Requires familiarity with models:* users need considerable familiarity with the models and libraries before they can compose designs fluidly, and so there is a considerable initial overhead; they also need considerable familiarity with the interface;
- *Limitations to annotation:* users often have little freedom in adding annotation or commentary, which might be used to capture rationale, development notes, references, alternatives, and so on – and this reduces flexibility especially before the system is clear and complete.

The designers address some of these shortcomings with what some described as "fudges", e.g., using a model with labels altered, using a model in an unconventional way and annotating it, capturing two different views on the same drawing. The 'fudges' are evidence that the CAD system has shortcomings or imposes constraints that are important enough to overcome explicitly. They also reveal the sorts of qualities and facilities designers require, e.g.:

- The importance of *"handiness"* ("I need it now, but it's not in the library"), and
- Building syntactically incorrect things and then fixing it later (or not).

- Transporting habits or forms of expression from one system to another, for designers who use multiple CAD systems.

6. Conclusion

Conceptual-level reasoning is reflected in the sketches experts make when exploring early design ideas. Hence, we conducted this examination of a substantial corpus (1055 examples) of 'idea capture'. When allowed to choose freely (i.e., to grab a pencil and the back of an envelope, or to step over to a whiteboard), designers use a limited set of representations, some of which refer to the formal representations from their discipline, and others of which are either generic or extremely versatile.

Designers use free sketches for several purposes which are not well supported by existing CAD systems:

- indicating *provisionality* or deferral of decisions
- *juxtaposition:* mixing disciplines, representations, and levels of abstraction within one sketch
- drawing *scenarios:* use-oriented views of the whole system in context ('the big picture')
- freedom from prescription

Hence, the study offers a basic prescription for an idea-capture tool.

In addition, the observations and sketches also offer pointers about requirements for an idea-capture tool that supports collaborative design – all of the above, plus:

- simplicity, speed
- visibility (everyone needs to see it)
- highlighting (changing the physical characteristics, perhaps temporarily, to draw attention to the bit under discussion)
- identity (knowing who made the marks occasionally assists discussion)
- history (automating 'how did we get here?' via some sort of re-wind/re-play)
- context (keeping track of which discussion the material relates to – supporting the role of the record keeper in an effective team)
- ultimately, smooth transition to CAD.

Overall, designers' ephemeral and informal representations hold a great deal of information about their focus and reasoning during the capture of ideas in early design.

7. Acknowledgements

The author thanks the companies and designers, without whose participation the research would not have been possible. Thanks also to André van der Hoek, Alex Baker, and Helen Sharp. The research was conducted under EPSRC grant GR/J48689 (Facilitating Communication across Domains of Engineering), for which George Rzevski, Helen Sharp and the author were co-investigators. The research was supported in part by an EPSRC Advanced Research Fellowship AF/98/0597. The author is a Royal Society Wolfson Research Merit Award Holder.

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category			**relates to formal represen-tation**	**used alone**	**used on same page as other represen-tations**
1	A	algebra	●	●	●
2	B	bus (physical schematic)	●	●	●
3	C	curve (plot of a function)	●		●
4	D	design for a physical object or display		●	●
5	E	executable (source code)	●	●	●
6	F	frequency response	●		●
7	G	geometric drawing	●		●
8	H	hierarchical structure diagram			●
9	L	list (alpha-numeric)		●	●
10	M	map (plot of points in space)			●
11	N	numeric		●	●
12	P	pole/zero plot	●	●	●
13	S	schematic	●	●	●
14	SS	scenario sketch			●
14	T	timing diagram	●	●	●
15	W	waveform	●	●	●
16	X	doodle		●	●
18	Z	natural language notes			●

Table 1: Characteristics of representations used

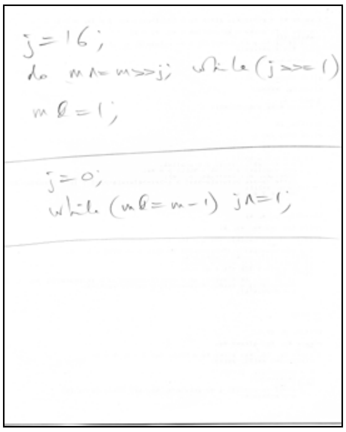

Figure 1: An example of an *executable:* an isolated coc fragment

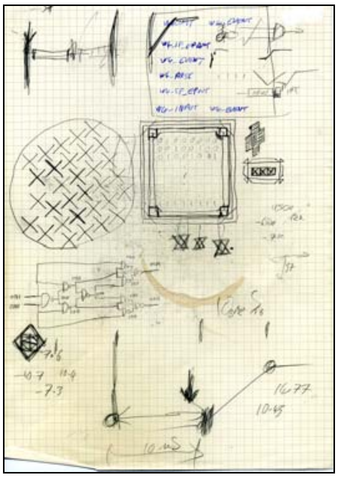

Figure 2: An example including *frequency response*, *schematic* and *executable* elements, as well as some *doodles*

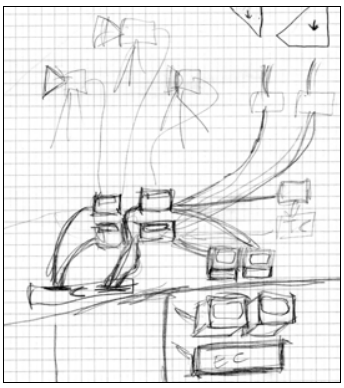

Figure 3: An example of a *scenario sketch*, extracted from a larger sheet.

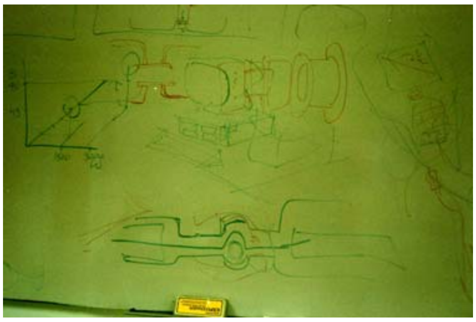

Figure 4: A whiteboard example with mixed representations.

Figure 5: An examples including *schematic* and *physical design* elements.

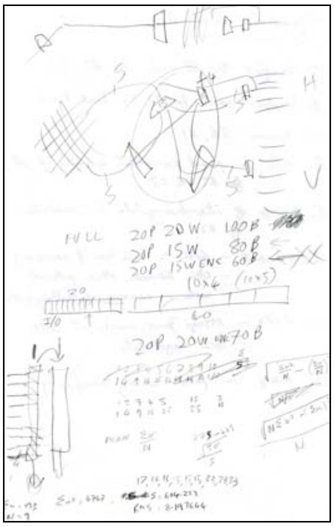

Figure 6: An example including *algebra*, *numeric*, *bus*, and *schematic* elements. Crossings-out are evident.