Representing Experimental Procedures through Diagrams at CERN's Large Hadron Collider: The Communicatory Value of Diagrammatic Representations in Collaborative Research

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Abstract: The aim of this paper is to elucidate the use and role of diagrams in the design of present day high energy physics experiments. To this end, drawing upon a prominent account of diagrammatic representations advanced by the cognitive scientists Jill Larkin and Herbert Simon, I provide an analysis of the diagrammatic representations of the data selection and acquisition procedures presented in the Technical Design Report of the ATLAS experiment at CERN's Large Hadron Collider, where the Higgs particle was discovered in 2012. Based upon this analysis, I argue that diagrams are more useful than texts in organizing and communicating the procedural information concerning the design of the aforementioned experimental procedures in the ATLAS experiment. Moreover, I point out that by virtue of their representational features, diagrams have a particular communicatory value in the collaborative work of designing the data acquisition system of the ATLAS experiment.

1. Introduction

In relatively recent years, quite a number of diverse case-studies concerning the use of *visual displays*—such as graphs, diagrams, tables, pictures, drawings, etc.—in both the physical and biological sciences have been offered in the literature of the history and philosophy of science (HPS)—see, e.g., Miller 1984; Lynch and Woolgar 1990; Baigrie 1996; Pauwels 2006. These case-studies have shown that visual representations fulfill important functions in both the theoretical and experimental practices of science, thereby emphasizing the *non-verbal* dimension of scientific inquiry that had been neglected by the traditional language-based conception of science, which takes the production, justification and dissemination of scientific knowledge to be essentially linguistic processes expressed in the form of scientific theories and hypotheses.[1]

The notion of diagrammatic representation has been long studied by cognitive scientists in relation to the issue of problem solving and thinking with diagrams, as well as in relation to the

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[1] This conception dates back to the writings of the logical positivists who characterized scientific discourse in terms of the logical and linguistic structures of scientific theories. Karl Popper, who was the earliest critic of logical positivism, as well as the philosophers of the *post-positivist* era in the philosophy of science—such as Norwood Russell Hanson, Thomas Kuhn and Imre Lakatos—also saw scientific inquiry mainly as a linguistic process driven by scientific theories and hypotheses.

analysis of cognitive processes involved in diagram interpretation and understanding (see, e.g., Cheng et al. 2001). However, even though historians and philosophers of science have drawn upon the resources of cognitive science to account for the cognitive aspects of scientific inquiry (see, e.g., Giere 1992), the HPS literature concerning the use of diagrams in scientific practice has not sufficiently benefited from the literature of cognitive science on reasoning with diagrams. The present paper is an attempt to make use of the resources of cognitive science to understand the role of diagrammatic representations in the current practice of experimental high energy physics (HEP).

Using diagrams to describe experimental procedures is an established practice in experimental HEP. For example, *block diagrams*[2] and *flowcharts*[3] were used in the technical design reports of the HEP experiments performed in the eighties and nineties, such as Large Electron-Positron Collider (LEP) experiments at CERN (see LEP Collaboration 1984) and the Collider Detector II (CDF II) experiment at Fermilab (see CDF II Collaboration 1996). In this paper, as a case study, I will examine the use of diagrams in the design of the data acquisition system of the ATLAS ("A Toroidal Large Hadron Collider Apparatus") experiment that has been running at CERN's Large Hadron Collider (LHC) in Geneva since September 2008 (see ATLAS Collaboration 2008). The ATLAS experiment is a *multi-purpose* experiment aimed to test the prediction of the Higgs boson by the Standard Model (SM) of elementary particle physics,[4] as well as to test a wide range of theoretical models—often referred to as the "models beyond the SM" (BSM models)—which have been offered as possible extensions of the SM in the literature of HEP (see, e.g., Ellis 2012). In 2012, the long-sought Higgs boson was discovered in the ATLAS experiment (ATLAS Collaboration 2012), as well as in the CMS experiment (CMS Collaboration 2012), which is the other multi-purpose experiment currently running at the LHC. As I shall show in this paper, different types of diagrams borrowed from the literature of System and Software Engineering (SSE)[5] are used in the ATLAS Technical Design Report (ATDR),[6] which is a technical document that contains the design information concerning the principal components and functions of the ATLAS data acquisition system (ATLAS Collaboration 2003). It is to be noted that the diagrams

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[2] A block diagram is a type of diagram that represents the main parts of a system as *blocks* connected through lines that show the relationships between different parts of the system.

[3] A flowchart is a type of diagram that represents the different steps of a process by connecting them through arrows.

[4] The SM of elementary particle physics consists of two gauge theories; namely, the unified theory of the weak and electromagnetic interactions, and the theory of quantum chromo-dynamics that describes strong interactions.

[5] SSE is a discipline concerned with the diagrammatic modeling of information systems for design and analysis purposes (see Booch et al. 2007; Hoffer et al. 2008). For a philosophical discussion concerning diagrammatic modeling in SSE, see Karaca 2012.

[6] The ATDR for data acquisition was reviewed by the Large Hadron Collider Experiments Committee (LHCC). The LHCC reviews the technical design reports of the experiments planned to run at the LHC, and makes recommendations to the CERN Research Board that takes final decisions regarding experimental proposals. The approved proposals become part of the CERN experimental program. It is stated in the minutes of the LHCC's 67th meeting held on 26-27 November 2003 that the LHCC recommended general approval of the ATDR to the CERN Research Board. It is also stated in the minutes of the 167th meeting of the Research Board held on 26 February 2004 that the ATDR was approved by the CERN Research Board. The minutes of the meetings of the LHCC and those of the CERN research board, as well as the information regarding these experimental committees, can be accessed at the URL: http://committees.web.cern.ch/Committees I am grateful to Peter Jenni, former spokesperson of the ATLAS experiment, for clarifying the review process of the ATDR, as well as for drawing my attention to the aforementioned minutes of the LHCC (personal communication, July 22, 2014).

of SSE I will analyze in this paper are much more complex than block diagrams and flow charts used in the technical design reports of the LEP and CDF II experiments.

Before I start discussing the use of diagrams in the case of the ATLAS experiment, in the next section, I will offer a brief overview of the HPS literature on the role of non-verbal reasoning in scientific practice.

2. HPS perspectives on non-verbal reasoning in scientific practice

In the HPS literature, the role of non-verbal reasoning in scientific practice has been most prominently studied by David Gooding in the context of scientific experimentation. Gooding has pointed out that even though "human agency is essential to both exploratory observation and experimental testing" (Gooding 1990a, p. 10) it has not been addressed by the standard philosophy of science that "has sought to reduce the interaction of theory and experiment to a logical relationship, that is, a relationship between propositions" (Gooding 1992, p. 65). In Gooding's view, however, this is an untenably simple view of the relationship between theory and experiment, as "[m]uch of what experimenters do involves nonverbal doing" (ibid., p. 66). Gooding's proposed solution to remedy this shortcoming is to elucidate what he calls the "procedural knowledge" of experiment that is manifest in the implementation of experimental procedures (Gooding 1990b, p.177).[7] To this end, Gooding has introduced a diagrammatic notation[8] for mapping experimental procedures and applied it to the case of Michael Faraday's electromagnetic induction experiments in order to characterize the human agency involved in performing these experiments in terms of Faraday's "conceptual and material manipulations" (Gooding 1990a,b). Using his diagrammatic notation and Faraday's laboratory notes, Gooding has provided, what he calls, the "experimental maps" of Faraday's manipulations during the course of his experiments—as shown in Figure 1. In Gooding's view, these maps make visible the human agency that is essential to perform Faraday's experiments.

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[7] Here, Gooding draws upon a standard distinction in epistemology—originally due to Gilbert Ryle (1945)—between two types of knowledge, namely, *declarative knowledge* ("knowing-that"), and *procedural knowledge* ("knowing-how"), which are respectively defined to be the knowledge of facts, things, or concepts, and the knowledge of performing actions.

[8] Gooding's notation is an elaboration of an earlier notation introduced by Ryan Tweney (1989) to map the procedures of Faraday's electromagnetic induction experiments.
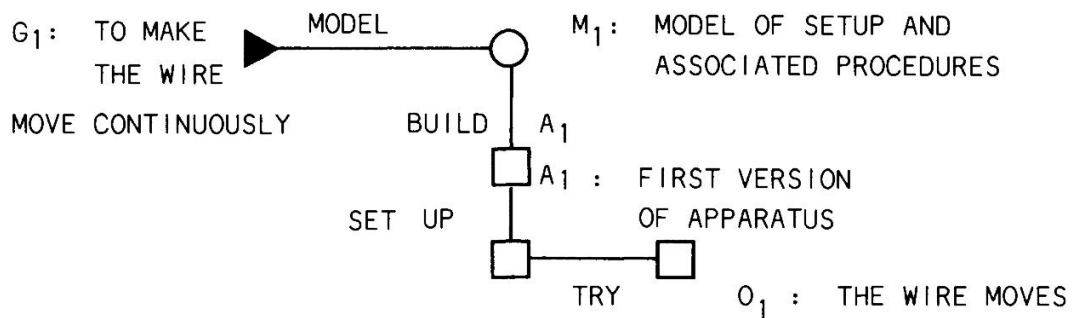
Figure 1: A Gooding map, and its caption, (Gooding 1990b, p. 180) that represents "Faraday's decision to build a setup, experiment with it, and represent and record outcomes" (ibid., p. 179). In this map, a "*square* denotes the outcome of manipulations in the material, phenomenal world (such as noticing, seeing, recording); and a *circle* denotes the outcome of mental operations (such as imagining, visualizing, describing, inferring, comparing) […] a solid triangle indicates a *change of* a major goal or method (e.g., from seeking evidence for one hypothesis to proving the methods used to obtain that evidence)" (ibid., p. 177-178).

Moreover, Gooding has argued that the visual imagery, which consists of *lines of force* and *magnetic curves*, Faraday created and used in his experiments was essential to his theorizing of the law of electromagnetic induction. In Gooding's view, through this visual imagery and the physical concepts it implied, Faraday was able to make the phenomenon of electromagnetic induction accessible to visual perception and eventually to verbal expression in the form of a law of nature.

Unlike Gooding, Nancy Nersessian has examined the role of *internal* representations associated with mental processes taking place during scientific reasoning, rather than *external* representations provided by visual displays. Nersessian has long advocated an approach, which she calls "cognitive-historical method," to analyze the problem solving practices of scientists (Nersessian 1992). This method is based on the idea that the resources of cognitive science can be used to elucidate some historical cases of scientific reasoning (Nersessian 2008, chap. 1). In accordance with her cognitive-historical method, Nersessian (ibid., sect. 4.1) has adopted the "mental models framework," which emerged in the literature of cognitive science in the 1980s following the seminal work of the cognitive psychologist Philip Johnson-Laird (1980, 1983).[9] Instead of subscribing to an already existing account of mental models, Nersessian has advanced her own account, which she calls the "minimalist mental modeling hypothesis" (Nersessian 2008, p. 128). According to this account, in certain problem solving tasks, human reasoning is carried out by means of the construction, implementation and manipulation of a mental model, which Nersessian defines as "an organized unit of knowledge that embodies representations of spatiotemporal relations, representations of situations, entities, and processes, as well as representations of other pertinent information, such as causal structure" (ibid.).

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[9] For an overview of different accounts proposed in the mental models framework, see Nersessian 2008, sect. 4.1.

Nersessian's main purpose in drawing upon the mental models framework is to understand how human reasoning is modeled during scientific inquiry. Nersessian has applied her account of mental modeling to James Clark Maxwell's work on electromagnetism. She has argued that Maxwell's train of thought leading to his derivation of the electromagnetic field equations can be seen as reasoning through a mental model (ibid., chap. 5). Nersessian has noted that various diagrams, such as the "vortex-idle wheel" diagram introduced by Maxwell, assisted him in his reasoning with the mental model he worked with. This last point concerns the issue of how mental models interact with external representations such as diagrams.[10] Nersessian has argued that there exist "correspondences between elements of mental models and elements represented in diagrams, [in the sense that] manipulating the components of a diagrammatic representation as one perceives it or acts on it can lead to corresponding transformations of the mental model (ibid., p. 161). In this way, according to Nersession, diagrams have the potential to facilitate the human reasoning process through interplay with mental models (ibid.).

In this paper, I will not address the issue of how scientists reason through mental models during scientific inquiry. Rather, in line with Nersessian's cognitive-historical method, I will elucidate the role of diagrammatic representations in the design of experimental procedures in the context of the ATLAS experiment. To this end, I will draw upon a prominent account of diagrammatic representations advanced by the cognitive scientists Jill Larkin and Herbert Simon (L&S) (1987). In passing, let me note that Nersessian has also drawn upon L&S's account to argue in what respects diagrammatic and propositional (sentential) representations differ from each other (Nersessian 2008, chaps. 4 and 5). But, she has not applied L&S's account to a case study to examine the role of diagrammatic representations in scientific practice.

3. L&S on differences between diagrammatic and propositional representations

In a seminal paper, entitled "Why a diagram is (sometimes) worth ten thousand words," L&S (1987) have contrasted diagrammatic representations with propositional representations in order to characterize how these two types of knowledge representation differ from one another with respect to reasoning involved in problem solving in domains such as physics and geometry. In L&S's account, a propositional representation is a "data structure in which elements appear in a single sequence" (ibid., p. 68), whereas a diagrammatic representation is a "data structure in which information is indexed by two-dimensional location" (ibid.). Based on these definitions, L&S suggest that the "fundamental difference between our diagrammatic and sentential representations is that the diagrammatic representation preserves explicitly the information about the topological and geometric relations among the components of the problem, while the sentential representation does not" (ibid., p. 66). Therefore, the distinction L&S draws between diagrammatic and propositional representations indicates that, unlike propositional representations, "[d]iagrams are a kind of *analogical* (or *direct*) knowledge representation mechanism that is characterized by a parallel (though not necessarily isomorphic) correspondence between the structure of the representation and the structure of the represented" (Kulpa 1994, p. 77).

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[10] The same issue has been also addressed in the literature of cognitive science; see, e.g., Scaife and Rogers 1996; Hegarty 2004; Liu and Stasko 2010.

L&S offer two main reasons "why a diagram can be superior to a verbal description for solving problems" (L&S 1987, p. 98). The first reason concerns what they call the "localization of information" (ibid.), namely, the *spatial* groupings of information that is necessary to solve a problem. In L&S's account, in diagrammatic representations, since "information is indexed by location in a plane, many elements may share the same location, and each element may be "adjacent" to any number of other elements" (ibid.). Diagrams thereby "can group together all information that is used together" (ibid.), and their use in domains of problem solving (such as geometry and physics) *substantially* reduces the need to search for the pieces of information relevant to make a problem solving inference. Unlike in diagrammatic representations, in propositional representations, since "the data structure is indexed by position in a list […] each element [lies] "adjacent" only to the next element in the list" (ibid.). As a result, the related pieces of represented information get increasingly separated from each other in propositional representations as the amount of information increases, thus working against the spatial localization of information (ibid., p. 69). This in turn makes propositional representations less efficient than diagrammatic representations to solve problems in domains such as physics and geometry.

The second main reason L&S offer concerns the *perceptual ease* provided by diagrams in problem solving. Since there exists a structural correspondence (not necessarily *one-to-one*), in terms of spatial relations contained, between the information and its diagrammatic representation, the latter has the ability to "automatically support a large number of perceptual inferences, which are extremely easy for humans" (ibid., p. 98). For instance, "when we draw a rectangle and its two diagonals, the existence of the point of intersection of the diagonals is inferred automatically—the point is created on the paper, accessible to perception" (ibid.). However, since no structural correspondence exists between spatial relations and their corresponding propositional representations, information regarding spatial relations is not readily available to visual perception when represented by texts and needs to be inferred from the syntactic and semantic structures of sentences, thus making texts less efficient than diagrams in terms of the representation of spatial relations.

In L&S's account, two "representations are informationally equivalent if all of the information in the one is also inferable from the other, and vice versa […] Two representations are computationally equivalent if they are informationally equivalent and, in addition, any inference that can be drawn easily and quickly from the information given explicitly in the one can also be drawn easily and quickly from the information given explicitly in the other, and vice versa" (ibid., p. 67). In L&S's account, diagrammatic and propositional representations are not *computationally* equivalent, in that by virtue of spatial localization of information and perceptual ease provided by diagrams, the ease and rapidity of making a problem-solving inference through diagrammatic representations are considerably greater than through propositional representations. It is important to note that, in L&S's account, as the title of their 1987 paper also indicates, the above-mentioned virtues of diagrams should not be taken to imply that they are always superior to propositional representations for problem solving. Rather, in order for a diagram to be useful in the problem-solving process, it must be constructed in such a way to take advantage of the above-mentioned virtues of diagrammatic representations (ibid., pp. 98-99).

The above overview suggests that L&S provides a ground not only to account for the use and function of diagrammatic representations in experimentation, but also to compare the diagrammatic and propositional representations of experimental procedures to assess their relative effectiveness. In this paper, I shall make use of L&S's account to examine the diagrammatic representations of data selection and acquisition procedures presented in the ATDR, as well as to compare them with the corresponding textual descriptions. It is worth noting that typically relatively simple examples of diagrams, such as those used in physics and geometry textbooks, have been examined in the literature of cognitive science. In this sense, the diagrams of SSE used in the ATDR present a novel case in which to analyze the differences between diagrammatic and propositional representations, in that the foregoing diagrams are far more complex and standardized than those diagrams previously considered in cognitive science studies.

4. Description of the ATLAS data acquisition system through diagrams

In order for a HEP experiment to achieve its intended objectives, what are often called *interesting events*[11] need to be acquired during the process of data acquisition. Interesting events are those collision events that are considered to have the potential to serve the objectives of the experiment. Given that in HEP experiments, new particles are detected through their *signatures*, i.e., stable decay products, the collision events that contain the signatures of novel particles are considered to be interesting in the aforementioned sense. In the case of the ATLAS experiment, interesting collision events refer to those collision events that contain the signatures of the Higgs boson predicted by the SM and those of the novel particles predicted by the BSM models, such as *superpartner* particles predicted by supersymmetric models. The foregoing signatures include single particles, namely, photons and leptons[12] with transverse momentum (p_T)[13] at or above $O(10)\ GeV$, and jets with p_T at or above $O(100)\ GeV$, as well as missing or total transverse energy (E_T) at or above $O(10)\ GeV$.[14]

The process of data acquisition in the ATLAS experiment is carried out in three stages by using trigger systems that perform an online selection (i.e., while proton beams are colliding inside the LHC) of interesting events according to a set of pre-determined selection criteria called a *trigger menu*.[15] The selection criteria are given in terms of the aforementioned signatures. Table 1 illustrates a sample trigger menu that consists of some of the major data selection criteria used in the ATLAS experiment. Each selection signature (or criterion) given in the left column of Table 1 is denoted as '$NoXXi$.' Here, 'N' denotes the minimum number of signatures required for a

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[11] In the terminology of experimental HEP, a collision event is defined to be a set of particle interactions that occur as a result of one *bunch crossing*, which takes place when two beams of particles collide with each other inside the particle collider.

[12] A lepton is a spin ½ particle that interacts through electromagnetic and weak interactions, but not through strong interactions. In the SM, leptons include elementary particles including electron, muon, tau, and their respective neutrinos.

[13] Transverse momentum (p_T) is the component of the momentum of a particle that is transverse to the proton-proton collision axis inside the ATLAS detector, and transverse energy (E_T) is the energy due to transverse momentum.

[14] For a thorough discussion of interesting events in the case of the ATLAS experiment, see ATLAS Collaboration 2003, sect. 4.

[15] For the details of how selection criteria are determined, see ATLAS Collaboration 2003, chap. 4. For a philosophical discussion, see Karaca (forthcoming).

particular selection, and 'o' denotes the type of the selected signature; e.g., 'e' for electron; 'γ' for photon; 'μ' for muon; 'xE' for missing E_T; 'E' for total E_T; and 'jE' for total E_T associated with jet(s). The label 'XX' denotes a lowest E_T (in units of GeV) for the signature under consideration, and 'i' denotes an isolation requirement for the given signature. For example, the selection criterion '$e25i$' in Table 1 amounts to the requirement of at least one isolated electron with an E_T at or above 25 GeV. The right column of Table 1 shows the processes predicted by the SM and the BSM models to which the selection signatures in the left column of the same table are relevant (for details, see ATLAS Collaboration 2003, sect. 4.4.1).

Selection signature	Examples of physics coverage
e25i	W → ev, Z → ee, top production, H → WW$^{(*)}$/ZZ$^{(*)}$, W',Z'
2e15i	Z → ee, H → WW$^{(*)}$/ZZ$^{(*)}$
μ20i	W → μν, Z → μμ, top production, H → WW$^{(*)}$/ZZ$^{(*)}$, W',Z'
2μ10	Z → μμ, H → WW$^{(*)}$/ZZ$^{(*)}$
γ60i	direct photon production, H → γγ
2γ20i	H → γγ
j400	QCD, SUSY, new resonances
2j350	QCD, SUSY, new resonances
3j165	QCD, SUSY
4j110	QCD, SUSY
τ60i	charged Higgs
μ10 + e15i	H → WW$^{(*)}$/ZZ$^{(*)}$, SUSY
τ35i + xE45	qqH(ττ), W → τν, Z → ττ, SUSY at large tan β
j70 + xE70	SUSY
xE200	new phenomena
E1000	new phenomena
jE1000	new phenomena
2μ6 + μ$^+$μ$^-$ + mass cuts	rare b-hadron decays (B → μμX) and B → J/ψ (ψ')X

Table 1: Major selection criteria used at the ATLAS experiment. (Source: ATLAS Collaboration 2003, p. 38)

The first stage of the data acquisition process is carried out by the level-1 trigger system that performs a *crude* selection of potentially interesting events from the collision events detected by the calorimeter and muon detectors, which are the components of the ATLAS detector system. The level-1 trigger system produces a trigger decision within 2.5 microseconds and thereby reduces the LHC event-rate frequency of 40 MHz down to the range of 75-100 kHz. For future reference, note that the regions in the ATLAS detector that contain signals for interesting events

are called "regions of interest" (RoIs) and that the RoIs and the energy information associated with the signals detected inside the RoIs are together referred to as the "RoI data."

In addition to the calorimeter and muon detectors, the tracking detectors are also used in the ATLAS experiment.[16] Since the event rate is so high and thus the trigger decision time is so short, it is technologically impossible for the tracking detectors to determine particle tracks quickly enough for the level-1 event selection. Only the *hit points* produced by particles inside the tracking detectors could be recorded. These space points are later assembled by software algorithms in order to determine particle tracks. As a result, the data from the tracking detectors are not used directly by the level-1 trigger system for event selection. Moreover, due to the shortness of the level-1 trigger-decision time, even though the hit points are recorded, they are not completely read out from the tracking detectors during the level-1 selection. This means that the information (i.e., in terms of location in the detector, and p_T or E_T for each particle or jet contained, or associated missing E_T) necessary to fully specify a selected event is fragmented across the individual detectors of the ATLAS detector system, and all pieces of this fragmented information are not assembled yet so as to fully describe a selected event. Therefore, the full description of the event is not yet known, and as a result, the level-1 event selection is performed without *full granularity*, i.e., without the availability of data from all the channels of the individual detectors.

The level-2 and level-3 trigger systems, which are jointly called the High Level Trigger (HLT) system, have longer trigger decision times and thus can provide much finer selections of interesting events than the level-1 trigger system. The event-accept rates of these trigger systems are respectively around 2 kHz and 200 Hz.[17] Unlike the level-1 trigger system that is hardware-based, the HLT system is software-based, meaning that event selections are performed directly by specialized software algorithms. In the diagram shown in Figure 2, which illustrates what is called a *communication diagram*[18] in SSE, the sub-units of the HLT system are represented as *objects*, and the messages exchanged among them are represented by text-labeled solid arrows. As shown in this communication diagram, the level-2 event selection begins when the sub-unit called "level-2 supervisor," denoted as "LVL2Supervisor", sends the results of the level-1 selection to the sub-unit called "level-2 processing," which is denoted as "LVL2Processing Unit." Unlike the level-1 trigger system, the level-2 trigger system uses the RoI data processed by the sub-unit called "Read-out System" (ROS) from all the sub-detectors of the ATLAS detector

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[16] In HEP experiments, the tracking detectors are used to determine particle tracks as well as to measure the momenta of electrically charged particles by means of the curvatures of their tracks in a magnetic field.

[17] These and previous event-accept rates are valid for early data taking at the LHC, as they have later changed significantly.

[18] In SSE, a *communication diagram* (also called a *collaboration diagram*) provides a diagrammatic representation of the ways in which a particular set of *objects* exchange information with each other during a certain period of time in order to achieve a common purpose (see, e.g., Booch et al. 2007, sect. 5.14). The term *object* is used in SSE to denote entities that perform specific tasks whenever they are called upon by messages. Each rectangular box in the communication diagram shows a particular object, the name of which appears in the same box. A communication diagram does not include a time axis, because it does not specifically focus on the temporal order of messaging among objects. In a communication diagram, messages exchanged among objects are shown by number-tags and text-labeled arrows. The temporal order of messages is indicated by the increasing order of number-tags. If a message prompted other messages in a system, the prompted messages are nested inside the prompting one.

with *full granularity*. The communication between the LVL2Supervisor and the LVL2Processing is shown by the message labeled "1" in Figure 2.
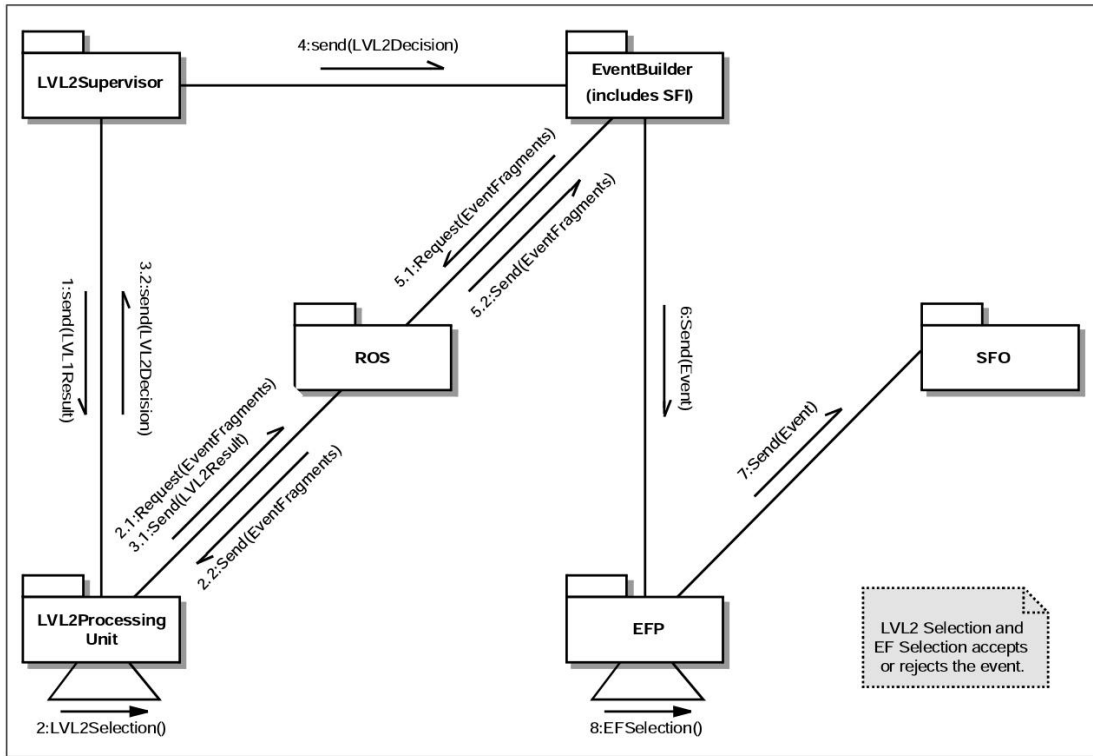

Figure 2: The communication diagram for the implementation of the HLT system in the ATLAS experiment. (Source: ATLAS Collaboration 2003, p. 126, Figure 9-2)

The event fragments, which are temporarily stored in the ROS, are accepted to the level-2 selection in small amounts. This way of performing event selection is called the *seeding mechanism* in the ATDR (ATLAS Collaboration 2003, sect. 9.5.3.1). Note that if event fragments were accepted at once, this would considerably diminish the level-2 trigger decision time and thus render the selection process *ineffective*. The seeding mechanism is initiated by the transmission of the message labeled "2.1" by the LVL2Processing unit to the ROS. Upon the reception of this message, the ROS sends to the Level2Processing Unit a subset of the event-fragments data, namely, the information regarding the locations (in the detector), momenta, and energies of the events selected at the level-1 selection. This communication between the Level2Processing Unit and the ROS is represented by the message labeled "2.2" in the communication diagram. The LVL2Processing unit sends the information regarding the events accepted by the level-2 trigger system back to the ROS. The LVL2Processing unit also sends the same information to the LVL2Supervisor. The foregoing communications are shown respectively by the messages labeled "3.1" and "3.2" in the communication diagram. The LVL2Supervisor forwards the same information, indicated by the message labeled "4", to the sub-unit called "Event Builder," which, as shown by the message labeled "5.1", requests from the ROS the

event-fragments data for the events selected by the LVL2Processsing unit. Upon this message, as shown by the message labeled "5.2", the ROS sends the event fragments to the Event Builder. The component called "Sub-Farm Input" (SFI) of the Event Builder assembles the event fragments associated with each selected event into a single record. Therefore, at this stage, the full description of each selected event is available. As shown by the message labeled "6", the events that have been built are then passed to the sub-unit called "Event Filter Processor" (EFP), through which the level-3 event selection, which is also called "event filter" (EF) selection, is carried out by specialized software algorithms. As shown by the message labeled "7", the events that have passed the level-3 selection are then sent to the sub-unit called "Sub-Farm Output" (SFO) for permanent storage and offline data analysis.[19]

Note that the details of the level-2 and level-3 selection processes are not shown in the communication diagram in Figure 2. These selection processes are carried out by the Event Selection Software (ESS) system, which is a software component of the HLT system (ATLAS Collaboration 2003, sect. 9).[20] The details of the level-2 selection process are shown in the diagram in Figure 3, which illustrates what is called a *sequence diagram*[21] in SSE. As shown in this sequence diagram, the level-2 selection of an event is carried out in a series of *steps* each of which consists of two stages. In the first stage, the event is partially reconstructed, meaning that the trigger elements (TEs)[22] associated with the event are refined and reconstructed by the *reconstruction algorithms* according to what is called the *sequence table* of the step. Each sequence in this table consists of an input TE and a reconstruction algorithm that is to be executed to refine and reconstruct an input TE into an output TE.[23] In the second stage, the event partially reconstructed undergoes a selection process based on what is called the *menu table* of the step that contains a list of the selection signatures required for this step.

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[19] Note that in the communication diagram shown in Figure 2, the correct number-tags for the messages "EFSelection" and "SendEvent" should be "7" and "8" respectively.

[20] For future reference, note that the following units to be mentioned in what follows, namely, Step Handler, Step Sequencer, Step Decision, Step Controller and Result Builder, are the software components of the ESS system that steers the HLT selection process.

[21] Note that the communication and sequence diagrams for the *same* system contain the same information. However, unlike a communication diagram, a sequence diagram focuses on the temporal order of messages exchanged among objects in a system (see, e.g., Hoffer et al. 2008, pp. 268–275). In a sequence diagram, time increases down the vertical axis. Each object in the system is shown by a rectangular box lying along the horizontal axis at the top of the diagram. What is called the *lifeline* of an object is denoted by either a dashed or a solid line emanating from that object and lying along the vertical axis. Each *thin* rectangular box emanating from an object and superimposed on the lifeline of the same object represents the time period during which an object performs a task. Message scripts are generally put just above the message arrows, and return messages are typically not shown, as they unnecessarily complicate sequence diagrams.

[22] A TE denotes one specific signature identified by the level-1 trigger system, e.g.,"$e25i$". A TE is said to be *active* if it has previously satisfied a selection signature at the level-1 selection, or at the previous step of the level-2 selection, if the step under consideration is not the first step of the level-2 selection.

[23] Reconstruction algorithms are a class of HLT algorithms that act on the RoI data with full granularity from all sub-detectors to find new features associated with input TEs, such as a track or an isolation requirement.
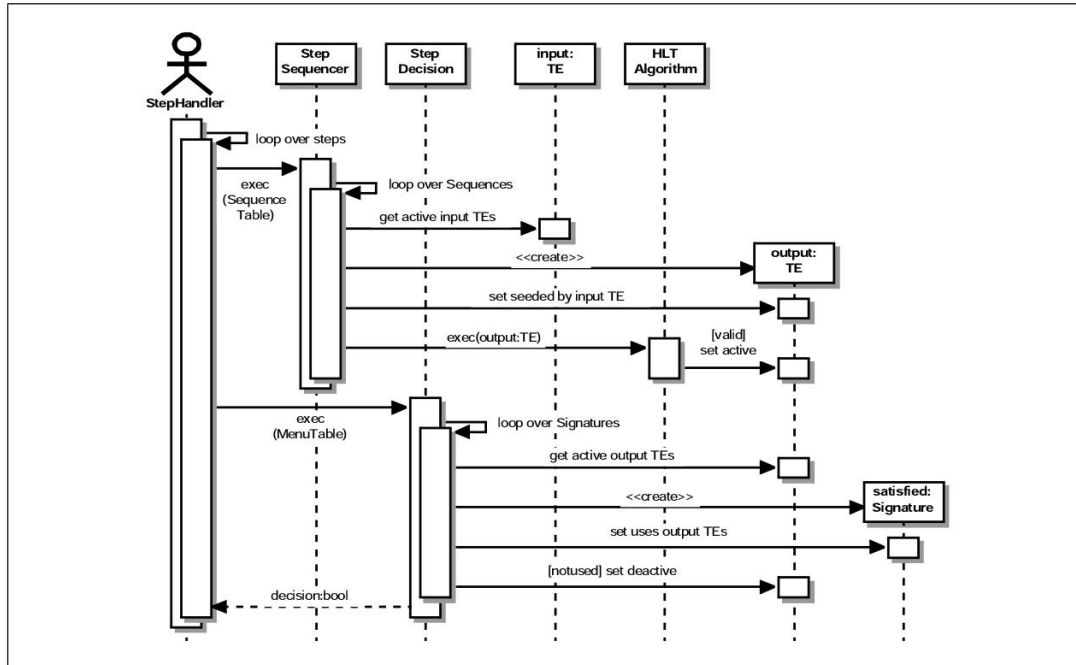
Figure 3: The sequence diagram for the implementation of the ESS system for the level-2 event selection in the ATLAS experiment. (Source: ATLAS Collaboration 2003, p. 150, Figure 9.21)

As shown in the sequence diagram in Figure 3, the Step Handler initiates the first stage of the level-2 selection by executing the Step Sequencer to access the list of the *active* input TEs associated with an event selected by the level-1 trigger system. The Step Sequencer next compares the list of the active TEs with the required TEs given in the sequence table of the step. For all matching TEs, the Step Sequencer executes the reconstruction algorithms to refine and reconstruct the input TEs into the *output* TEs according to the sequence table of the step. The Step Sequencer also creates the list of the output TEs for the implementation of the seeding mechanism discussed earlier. The Step Sequencer also marks each output TE as "seeded by input TE" depending on from which input TE it has been previously created. Then, it passes each output TE to the relevant *hypothesis algorithms*—another class of HLT algorithms—that decide whether the TE is valid, depending on whether its reconstructed features are consistent with its physics interpretation. For example, if a track or an isolation requirement associated with a TE is found by a reconstruction algorithm, then the relevant hypothesis algorithm determines whether this track or isolation requirement matches the physics interpretation of the TE. The hypothesis algorithms *activate* the validated TEs and discard the invalidated TEs by deactivating them.

As shown in the sequence diagram in Figure 3, the Step Handler initiates the second stage of the level-2 selection by calling the Step Decision to access the list of the active output TEs, i.e., the TEs validated by the hypothesis algorithms in the first stage of the level-1 selection. The Step Decision compares the list of the active output TEs with the required selection signatures given in the menu table of the step. For the TE combinations that match the selection signatures in the menu table, the Step Decision creates a list of the satisfied signatures that consist of those

12

matching TE combinations. The event is accepted for the next step by the Step Decision, if the TE combinations it contains satisfy at least one signature given in the menu table of the step; otherwise it is rejected and thus not considered for the level-3 selection. In the next step, only those TEs that have been used to satisfy at least one signature in the previous step are considered, and the others are discarded from further processing. The Step Decision sends the information regarding the decision about the event to the Step Handler that will initiate the next step configured with a different sequence table and a menu table. The level-2 selection of an event ends at the step where it is rejected, or it continues until all required steps are completed, indicating that the event is finally accepted for the level-3 selection.

If an event is accepted at the level-2 selection, the Step Controller executes the Result Builder to provide the information necessary to *seed* the level-3 selection. This includes all satisfied signatures and the associated TE combinations, as well as the level-1 RoI data. The Result Builder assembles all these data-fragments, and the results are subsequently used for the seeding of the level-3 selection. The level-3 selection is implemented and coordinated by the Step Handler in the similar way as the level-2 selection is carried out as shown in the sequence diagram in Figure 3. But, the level-3 selection differs from the level-2 selection in that the TEs are now the active TEs of the level-2 selection, and that more sophisticated HLT algorithms are used to achieve a much finer event selection. As has been mentioned previously, the events that have passed the level-3 selection are stored in the SFO for data analysis.

The above overview indicates that the process of data acquisition in the ATLAS experiment is essentially a selection process through which interesting collision events are selected in three stages by the ATLAS trigger systems. This selection process consists of various experimental procedures that are represented in the ATDR through communication and sequence diagrams borrowed from the literature of SSE.[24] As shown in Table 2, the communication and sequence diagrams shown in Figure 2 and 3 represent the *procedural information* regarding the implementation of the HLT and ESS systems, respectively. This procedural information includes both spatial relations, namely, directions of data-flows and those of messages exchanged, as well as temporal relations, namely, temporal order of data-flows and that of messages exchanged. In both of the aforementioned diagrams, the directions of data-flows and those of messages exchanged are represented as spatial relations, namely, text-labeled solid arrows. In the communication diagram, the temporal order of data-flows and that of messages exchanged are represented by the numerical order of the message number-tags. In the sequence diagram, the temporal order of data-flows and that of messages exchanged are represented by the vertical spatial order of text-labeled solid arrows.

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[24] The ATDR also uses other types of SSE diagrams. The procedures concerning the flow of various types of data between the HLT system and the level-1 trigger system, as well as between the HLT system and the external systems, including the LHC machine, the ATLAS detector system and the data storage unit, are represented by what is called a *context diagram* in SSE (see ATDR 2003, Figure 5-1, p. 48; for details about a context diagram in SSE, see Hoffer et al. 2008, chap. 7). Moreover, the procedures concerning how the HLT algorithms relate to and depend on each other are represented by what is called a *class diagram* (see ATDR 2003, Figure 9.18, p. 147; for details about a class diagram in SSE, see Booch et al. 2007, chap. 3 and sect. 5.7). I shall not discuss the use of the foregoing types of diagrams in the ATDR, as they are not necessary for the argument of the present paper.

ATLAS data selection and acquisition procedures and corresponding diagrammatic representations	Procedural relations represented by diagrams	Corresponding representing relations in diagrams	Linguistic diagrammatic elements and associated conventions	Symbolic diagrammatic elements and associated conventions
Implementation of the HLT system: communication diagram	Spatial relations: directions of data-flows and of messages exchanged among the units of the HLT system	Spatial relations: directions of text-labeled solid arrows among diagram units	Text labels: contents of messages and of data flows	Solid arrows: directions of solid-arrows denote directions of data-flows and of messages
	Temporal relations: temporal order of messages exchanged among the units of the HLT system	Numerical relations: numerical order of message number-tags		Message number-tags: numerical order of message number-tags denotes time order of messages
Implementation of the ESS system: sequence diagram	Spatial relations: directions of data-flows and of messages exchanged among the units of the ESS system	Spatial relations: directions of text-labeled solid arrows among diagram units	Text labels: contents of messages and of data-flows	Solid arrows: directions of messages and of data-flows
	Temporal relations: temporal order of data-flows and of messages exchanged among the units of the ESS system	Spatial relations: vertical spatial order of text-labeled solid arrows		

Table 2: Procedural relations in the ATLAS data acquisition system and their corresponding diagrammatic representations together with their linguistic and symbolic diagrammatic elements.

Since the foregoing spatial relations existing among the sub-units of the HLT and ESS systems are represented as spatial relations by the communication and sequence diagrams in Figure 2 and 3 respectively, there exists a *structural correspondence,* in terms of spatial relations contained, between the communication diagram in Figure 2 and the HLT system, as well as between the sequence diagram in Figure 3 and the ESS system. As shown in Table 2, the communication and sequence diagrams maintain the foregoing structural similarities through the use of both *symbolic* (i.e., consisting of a diagrammatic symbol) and *linguistic* (i.e., involving both syntactic and semantic structures) diagrammatic elements. These diagrams also make use of certain symbolic and linguistic elements for the representation of temporal relations.

It is to be noted that by virtue of the aforementioned structural correspondence, the spatial and numerical relationships contained in the aforementioned communication and sequence diagrams enable one to draw inferences about the spatial and temporal relationships found in the HLT and ESS systems of the ATLAS experiment. For example, the temporal order of the messages exchanged during the implementation of the HLT system can be inferred by examining the

numerical order of the message number-tags in the communication diagram in Figure 2. Incidentally, this last point indicates a similarity between the aforementioned diagrams and mental models, in that the latter, in Nersessian's account, also "embody and comply with the constraints of the phenomena being reasoned about, and thus enable inferences about these phenomena" (Nersessian 2008, p. 129).

5. Advantages of diagrams over texts for the representation of data selection and acquisition procedures in the ATLAS experiment

The use of communication and sequence diagrams in the ATDR is essential to presenting the data selection and acquisition procedures implemented in the ATLAS experiment. Both the communication diagram shown in Figure 2 and the sequence diagram shown in Figure 3 are presented in the main text of the ATDR, rather than in an appendix, to introduce, respectively, the procedures concerning the implementation of the HLT and ESS systems.[25] In the main text of the ATDR, each of the foregoing diagrams is immediately followed by its corresponding textual description (see, ATLAS Collaboration 2003, p. 126 and pp. 150-151, respectively). These textual descriptions are provided in the ATDR in a very similar manner as presented in Section 4 of the present paper. A comparison of the communication and sequence diagrams with their corresponding textual descriptions indicates that all the procedural information (regarding the implementation of the HLT and ESS systems) that can be inferred from the communication and sequence diagrams can also be inferred from their corresponding textual descriptions, and vice versa. This suggests that the foregoing diagrammatic and propositional representations of the data acquisition and selection procedures implemented in the ATLAS experiment are, to use L&S's terminology, *informationally equivalent*.

It is also worth noting that unlike the communication and sequence diagrams in Figure 2 and 3, the corresponding textual descriptions, in addition, include some short explanations concerning the details of the HLT and ESS systems. These explanations are intended to provide the users of the ATDR with the information regarding certain key considerations underlying the design of the HLT and ESS systems, rather than regarding their implementation in the ATLAS experiment. In this sense, they are not essential to the (textual) descriptions of the implementation of the foregoing systems. For example, the textual description concerning the implementation of the HLT system (following the communication diagram in Figure 2) includes an explanation, which is similar to the explanation given in Section 4 of the present paper, as to why the seeding mechanism underlying the level-2 event selection is necessary for the HLT process (see ATLAS Collaboration 2003, p. 122). Note that this explanation does not include any description at all as to how the seeding mechanism is implemented in the HLT system. Rather, it involves the primary consideration as to why the seeding mechanism in the level-2 selection is necessary. For that reason, the foregoing explanation about the seeding mechanism is not essential to the textual description concerning the implementation of the HLT system.

The fact that the communication and sequence diagrams and their corresponding textual representations are informationally equivalent does not mean that they are also *computationally*

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[25] This is also true for the context and class diagrams used in the ATDR.

equivalent—in the sense of L&S's account. In what follows, I shall argue that the diagrammatic representations of the data selection and acquisition procedures implemented in the ATLAS experiment are computationally more efficient than the textual descriptions of the same procedures. To this end, I shall first note that, as indicated by Table 2, the spatial and temporal procedural relations that exist in the HLT and ESS systems are represented as spatial and numerical relations by the communication and sequence diagrams in Figure 2 and 3. The foregoing spatial and temporal procedural relations thereby become *directly* accessible to visual perception. However, the same spatial and temporal procedural relations must be inferred from the linguistic (i.e., syntactic and semantic) structures involved in propositional representations when they are textually described. As indicated by Table 2, the size of the set comprising the linguistic and symbolic diagrammatic elements and their associated conventions used by the communication and sequence diagrams in Figure 2 and 3 to represent spatial and temporal procedural relations within the HLT and ESS systems is far smaller and less detailed than the size of the set comprising the linguistic elements (such as words, verbs and propositions) and their associated rules and conventions used by texts to represent the same procedural relations. Therefore, it requires more cognitive effort to infer the foregoing relations from the textual descriptions than the communication and sequence diagrams. The above considerations regarding the differences between the diagrammatic and propositional representations of data selection and acquisition procedures in the ATLAS experiment illustrate the perceptual ease of inferring information from diagrams, as suggested by L&S's account.

Another advantage of diagrammatic representations over propositional representations as suggested by L&S's account is their ability to spatially localize the represented information. In order to see whether and how this feature of diagrammatic representations plays a role in the case of the communication and sequence diagrams in Figure 2 and 3, I shall first note that the various procedural relations represented by these diagrams can be regarded as related pieces of information about the data selection and acquisition procedures implemented in the ATLAS experiment. Second, in the textual descriptions of these experimental procedures presented in the ATDR, as the number of pieces of information to be represented increases, the number of sentences needed to represent these relations also increases. This in turn results in a gradual separation of the representing relations, and thus of the related pieces of information, from each other in the textual descriptions. In the remainder of this section, I shall argue that this is an *unsuitable* separation of the related pieces of the relevant procedural information in the sense that it makes the textual descriptions less efficient than the corresponding diagrammatic representations.

To this end, first, remember that, as pointed out by L&S, diagrams preserve spatial relations to the extent that they transform them into spatial relations. As a direct result of this feature, in the communication and sequence diagrams in Figure 2 and 3, the incoming and outgoing messages associated with a particular unit in the HLT and ESS systems lie adjacent to each other and in the proximity of this unit. This illustrates spatial localization of information by diagrammatic representation—in the sense of L&S's account. Therefore, in order to extract the information regarding the incoming and outgoing messages associated with a particular object from the communication and sequence diagrams, it is sufficient to check only the proximity of the object about which the foregoing information is sought, because all the messages relevant to the required information are grouped in the proximity of this particular object. This in turn means

that, in both the communication and sequence diagrams shown in Figure 2 and 3, the information regarding the incoming and outgoing messages associated with a particular unit within the HLT and ESS systems can be obtained directly by checking the contents of the text labels for the message arrows coming in and out of the object representing this particular unit. For example, in order to extract the information regarding the communication between the ROS and the LVL2Processing and EventBuilder units from the communication diagram shown in Figure 2, it is sufficient to check the contents of the message-texts associated with the ROS, i.e., the incoming message-texts labeled "2.1", "3.1" and "5.1", and the outgoing message-texts labeled "2.2" and "5.2".

In contrast, in the textual descriptions of the HLT and ESS systems, the sentences representing the incoming and outgoing messages associated with the individual units in these systems are spread throughout the textual descriptions, rather than grouped together, because, unlike diagrammatic representations, propositional representations do not preserve spatial relations. As a result, in the foregoing textual descriptions, the sentences relevant to the messaging information associated with an individual unit do not necessarily succeed one another without intervening sentences whose contents are not relevant to the messaging information. This means that in order to extract the messaging information of interest from the corresponding textual description, it is necessary to check also the content of each of these intervening sentences. For example, the message texts labeled "3.2" and "4" shown in the communication diagram in Figure 2 are neither incoming nor outgoing messages for the ROS. Therefore, it is not necessary to take them into account in extracting the messaging information associated with the ROS from the communication diagram. However, in extracting the same messaging information from the corresponding textual description, it is necessary to check the contents of the sentences representing the foregoing messages, as they lie among the sentences representing the message texts labeled "2.1", "2.2", "3.1", "5.1", "5.2", which are relevant to the messaging information of interest. The same is true in the case of the messaging information associated with the LVL2Supervisor unit, for which, as shown in the communication diagram in Figure 2, the message-text labeled "3.2" is the incoming message, and the message-texts labeled "1" and "4" are the outgoing messages. Only the foregoing message-texts need to be considered in order to extract the messaging information of interest from the communication diagrams. However, in order to extract the same messaging information from the corresponding textual description, the contents of the sentences representing the message-texts labeled "2", "2.1", "2.2" and "3.1", which are not relevant to the messaging information of interest, also need to be taken into account, as they lie between the sentences representing the message-texts labeled "3.2" and "4".

The sequence diagram in Figure 3 also illustrates spatial localization of information by diagrammatic representation. This diagram represents the procedural information as to how the first and second stages of the level-2 event selection are carried out by the aforementioned components of the ESS system. The related pieces of this procedural information for each stage of the level-2 selection can be found in the same proximity in the sequence diagram, in that the message-texts relevant to the above information for each of the relevant components of the ESS system lies in the proximity of the thin rectangular box representing the time period during which the component of interest operates. Therefore, in the case of the sequence diagram, the inference leading to the above procedural information is *direct*, in the sense that the related pieces of this information can be perceived at once by checking the dashed lines that represent the time lines

for the relevant components of the ESS system. The above procedural information can also be inferred from the corresponding textual description in the ATDR. However, in this case, the inference leading to the information of interest is *indirect*, in that it cannot be drawn until the contents of all the sentences in the textual description are checked and thereby the relevant messaging information for each of the components of the ESS is identified.

The above discussion illustrates the spatial localization feature of diagrammatic representations in the cases of the communication and sequence diagrams used in the ATDR. In both of these diagrams, the message-texts used together to infer a conclusion regarding the communication among the different units in the HLT and ESS systems are found in close proximity to each other and also to the units under consideration. The advantage offered by this localization feature is that it substantially facilitates the cognitive process of inferring the information regarding the messaging among the units of the HLT and ESS systems. In contrast, in the textual descriptions of these systems presented in the ATDR, the sentences used together to infer the same messaging information are separated from each other in ways that substantially complicate the inference process.

The discussion in this section suggests that by virtue of their representational features, namely, perceptual ease and spatial localization, the communication and sequence diagrams used in the ATDR are better suited for the representation of the HLT and ESS related procedures than their corresponding textual descriptions, even though diagrammatic and textual descriptions are informationally equivalent in this case. It is to be noted that the aforementioned advantages of the diagrams of SSE apply only if all the rules and conventions of these diagrams are known to the users of the ATDR. Incidentally, this last point relates to the notion of *visual literacy*, which Daniel Rothbart has illustrated in the context of the design of experimental instruments. Rothbart has remarked that "[e]xperiments in contemporary research are often depicted through visual language, based on schematic drawings associated with an instrument's design" and that this requires visual literacy about diagrams, namely, that one must know what the individual symbols stand for in a given diagram in order to extract the relevant information from this diagram. (Rothbart 2003, p. 239). In a similar way, the present-case study suggests that extracting the procedural information concerning the ATLAS data acquisition system from the diagrams presented in the ATDR requires visual literacy about these diagrams. This point is especially important for the training of newcomers, especially young experimenters, to the ATLAS Collaboration, as these diagrams are also used to train them about the essential features of the ATLAS data acquisition system.

6. Conclusions

In this paper, I have shown that the procedural information represented by the communication and sequence diagrams in the ATDR illustrates how the data selection and acquisition procedures are carried out by means of software and hardware based automated devices in a large-scale HEP experiment. Since the foregoing diagrams of SSE are used in the ATDR to represent experimental procedures, in terms of the content of diagrammatic representations, the present case study differs from much of the recent philosophical studies that have examined various types of diagrams used to represent scientific claims about natural phenomena such as hypotheses, models and mechanisms. The general line of argument in these studies is that in scientific

practice there are cases in which diagrammatic representations are more appropriate for scientific explanation and model construction than propositional representations (see, e.g., Perini 2005; Goodwin 2010; Barberousse 2013; Sheredos et al. 2013). Some of these recent studies have explicitly drawn upon the localization feature of diagrammatic representations, as suggested by L&S's account (see, e.g., Bechtel and Abrahamsen 2005; Jones and Wolkenhauer 2012). Unlike the foregoing studies that are concerned with the epistemic value of using diagrams in representing scientific claims, the present case study suggests that diagrams are more appropriate than texts to represent the procedural information necessary to perform a large-scale HEP experiment, such as the ATLAS and CMS experiments at CERN's LHC.

An important implication of the above conclusion concerns the practical value of using diagrams in the ATDR for the collaborative work of designing the ATLAS data acquisition system. The procedures of this system are carried out jointly by internal and external research groups (for details, see ATLAS Collaboration 2003, sect. 17), as the system consists of three different trigger systems that are connected to the external systems such as the ATLAS detector system and the CERN data management system. This suggests that the collaborative work of designing the ATLAS data acquisition system had both internal stakeholders, such as trigger groups, and external stakeholders, such as detector operation and data analysis groups. Given that the procedural information represented by both texts and the diagrams of SSE in the ATDR involves the design requirements for the data selection and acquisition procedures in the ATLAS experiment, an *efficient* communication of the foregoing procedural information among the stakeholders was necessary in order for the collaborative design work to achieve its intended objectives. The analysis offered in the previous section shows that by virtue of their representational features, namely, perceptual ease and spatial localization of information, the cognitive process of inferring the procedural information regarding the data selection and acquisition procedures in the ATLAS experiment from the diagrams of SSE is substantially less complex than the cognitive process of inferring the same procedural information from their corresponding textual descriptions. Therefore, the present case study suggests that the diagrams of SSE used in the ATDR were better suited than their corresponding textual descriptions to provide a medium for *efficient* communication of the relevant procedural information among the stakeholders of the collaborative work of designing the ATLAS data acquisition system.

The above considerations indicate an important difference between the diagrams of SSE examined in this paper and Gooding's maps, despite the fact that they both represent experimental procedures. It is to be noted that Gooding's maps are aimed at a *diagrammatic reconstruction* of the procedures of Faraday's experiments that eventually led him to theorize the law of electromagnetic induction. In this sense, Gooding's maps are part of a *retrospective analysis* of Faraday's experiments on electromagnetic induction, rather than being an essential part of these experiments. Unlike Gooding's maps, the foregoing diagrams of SSE have been an essential part of the instrumentation needed to carry out the ATLAS experiment, in that they have been used as *visual tools* in the collaborative work of designing the data acquisition system of this experiment. Moreover, as I have argued above, by virtue of their representational features, these diagrams have served an important communicatory function in the aforementioned

collaborative design work.[26] Therefore, the conclusions of the present paper go beyond illustrating Gooding's idea that the procedural aspects of an experiment can be elucidated through diagrammatic representations of experimental procedures. They also show that these representations have a particular communicatory value in the practice of experimental HEP.

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[26] Note that the diagrams of SSE used in the ATDR can also be used retrospectively to optimize the ATLAS data acquisition system.

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