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Developing Analytic Thinking Skills in an Engineering Course using an Ethnographic Approach

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ABSTRACT

CONTEXT

Graduating engineers will be expected to make meaningful contributions in their professional employment. With engineering becoming increasingly multidisciplinary and skill diverse, students face significant challenges in developing the required knowledge base. A common difficulty for students is understanding complex and advanced technical engineering topics, a task that is not inherently easy. Despite a wealth of pedagogical techniques for addressing these problems, an underutilised resource is the learning and teaching practices used outside of engineering.

PURPOSE OR GOAL

This paper examines how ethnographic principles can be successfully adapted to improve learning in technical engineering subjects. An ethnographic approach focuses on subject domain detail and, using a constructivist approach, assists in building mental models that form a crucial ingredient of expert understanding. The longer-term aim is to improve awareness of innate capacities, engagement with subject domains and lifelong learning skills development. The research question was to determine how such an approach can be used in practice and evaluate its effectiveness.

APPROACH OR METHODOLOGY/METHODS

The method of implementation of the ethnographic approach was to adopt analytical thinking and writing methods from the book Writing Analytically (Rossenwasser & Stephen, 2019). The conceptual leap made was to extend verbal text representation to include multimodal texts including any symbolic representation of information such as mathematics, computer code and diagrams. A series of tasks and exercises were applied using scaffolding and constructivist principles. The approach was called analytic thinking, a concept that students could easily relate to. Cognitive perspectives were used to analyse difficulties of understanding, and Bloom's taxonomy was used to frame the approach in the broader learning context.

ACTUAL OR ANTICIPATED OUTCOMES

The approach was tested in a third-year undergraduate unit on random processes using class exercises and formal assignments. Qualitative evaluation of final examination results showed improvement and adaptability in solving complex problems compared to previous offerings. A student survey showed the techniques scored highly, just under the worthwhileness of class exercises and worked problems.

CONCLUSIONS/RECOMMENDATIONS/SUMMARY

By utilising analytical exercises that complement subject content delivery, it was demonstrated that understanding a subject's internal logic and complex and advanced material could be improved. The approach has strong student engagement and interaction. It provides a means of including more advanced material into the curriculum. It increases students' self-capacities, self-awareness, metacognition, and life-long learning skills.

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KEYWORDS

Engineering pedagogy, ethnography, analytic thinking, cognitive

Introduction

Graduating engineers will be expected and required to make productive and meaningful contributions in their future professional employment in which “they have to work with novel technologies, with a diversity of people around the world, as part of highly interdisciplinary teams, and on projects that are complex both in scale and expertise” (Johri, Olds, & O’Connor, 2014). With the pressure of such demands, students face significant challenges in developing the knowledge base and capabilities demanded. These challenges, in the context of a unit of study in a program, may be manifest as barriers (“walls”) to understanding as ideas become more complex and problem difficulty increases. In addition, problems may occur in subsequent courses, such as ‘delayed learning’ with students only coming to understand a concept in a later unit what was expected to be learnt in an earlier unit (Entwistle, 2009) (p. 95). The learning experiences of such problems for both students and instructors will be frustration and dissatisfaction with a consequent diminishing of lifelong learning skills.

A source of difficulty for learning is that subject areas often have long histories that have produced concepts and arguments with many subtleties. Newcomers to a subject domain often have trouble determining what is relevant and what is extraneous. Consequently, the subject content is not inherently easy, especially in middle and later year technical units where students need effective strategies to manage and understand significant amounts of detail. Some well-known pedagogical techniques for addressing learning problems include Bloom’s taxonomy, Kolb’s experiential learning (Kolb, 2014) and the threshold concept approach (Cousin, 2006). However, an underutilised resource is the learning and teaching practices utilised in areas outside of engineering. In particular, this paper examines how ethnographic principles can be adapted successfully to overcome difficulties in understanding and improve the learning of complex and advanced material in a technical engineering course. Ethnography involves the study of social systems and practices where immersion in an environment and attention to detail is the primary means of discovery. (Hammersley, 2019). Ethnographic research methods (see, e.g., (Blommaert & Jie, 2020)) are widely used in anthropology, organisational research and many other social research areas. In engineering education, ethnographic methods have been used to study the practices of professional engineers’ and students’ daily life (Godfrey, Johri, & Olds, 2014), (Case & Light, 2014). The distinctive feature of the current paper is the application of ethnographic principles to teaching technical content. Practical implementation of the approach is achieved by adopting the book Writing Analytically (Rosenwasser & Stephen, 2019), which has a strong ethnographic orientation. Following the book’s title, we call our approach *analytic thinking skills*, a familiar concept for students.

The primary research question is: How can an ethnographic approach be used in practice to improve the understanding of complex texts in teaching technical units in engineering? The paper critically evaluates the proposed solution and examines how it fits into broader educational aims. In the remainder of the paper, Section 2 discusses the difficulties of understanding complex and advanced texts, particularly from a cognitive perspective. Bloom’s taxonomy is used to frame the approach in the broader learning context. Section 3 presents the basic principles of the ethnographic approach. Section 4 describes the specific tasks and exercises used. Section 5 provides an example of the approach applied to a technical third-year undergraduate unit, including results. Section 6 presents a discussion of the results. Section 7 is the conclusion.

Difficulties of understanding subject matter

Direct expression of the difficulties of understanding complex material observed in the classroom includes: students explicitly articulating troubles in understanding, which, despite various attempts at clarification, remain unresolved; students asking questions later in the course about fundamental concepts that the instructor thought had been understood, only to be surprised that this was not the case; and, students revealing a lack of understanding of one concept when talking about another concept. A common cause of such learning deficiencies is the reliance on surface learning (Entwistle, 2009) (p. 95). This is manifested through learning by memorising, waiting for the instructor to provide solutions or only trying to obtain the gist of a topic. Such practices are often characteristic of the so-called ‘banking model of learning’ in which students deposit learning from the instructor into an account during the progress of a unit that is later withdrawn at the end, during the final assessment (Boerckel & Barnes, 1991).

Difficulties of understanding subject content from a cognitive science perspective are similar to the challenges faced in understanding expository texts (Britton, Glynn, & Smith, 2017). These challenges include calling upon large bodies of specialised knowledge, the need to recruit a range of reading processes such as determining the meaning of words, parsing and integrating text and limited availability of short-term memory that makes management of memory resources necessary. The unfamiliarity and unpredictability of a new text can produce fragmented and disorganised understanding. This can lead to the deployment of bottom-up reading strategies. Task difficulty is multifaceted; the paper by (Gilbert, Bird, Frith, & Burgess, 2012) lists seven indexes of task difficulty: (1) inability to even perform a task in the first place because of the early stage of development, (2) involvement of significant trade-offs between speed and accuracy, (3) dual-task interference caused by concurrent involvement in a second task, (4) vulnerability due to adverse factors such as age and fatigue, (5) requirement of high levels of executive control (e.g. to optimise goal-directed behaviour in novel situations, as opposed to routine procedures), (6) needing more subjective effort and motivation and (7) presence of higher levels of transformation of internal representations. Attention control is also essential to efficiently obtain relevant information (targets). Three general areas of attention control are activation, selection and control. Activation involves preparation for target detection through warning cues or vigilance to detect rarely occurring targets. Selection consists in locating the target in the sensory space using features or peripheral cues. Control involves determining whether and how to respond to a target.

Reducing difficulties of understanding

All of the above factors contribute to processing load. General methods for reducing processing load include increasing predictability, priming (which reduces memory fetching time), reusing recently retrieved items in working memory (locality), replacing the least used items first in working memory, signalling changes in text direction, and avoiding thrashing (repeated changing of tasks) (Graesser & Goodman, 2017). More broadly, highly structured knowledge structures such as schemas, mental models, themes and frames are activated when reading a passage. Comprehension can be viewed as the interaction between incoming passage information and schemas. Expert practice relies heavily on such structures to conduct the reasoning and problem-solving required for analysis, design, interpretation, diagnosis, and prediction (Newstetter & Svinicki, 2014). A constructivist approach (such as ethnography) provides mechanisms for building such mental models under the control of the learner. To proceed to more advanced levels of understanding, students need to see beyond the immediate content. Subject matter is usually mediated and recontextualised (Bernstein, 2000), and course designers need to know not just the content of a subject but also the theory of the content and how it is selected, framed and transformed (Deng, 2012). Reverse engineering this mediation is assisted by constructing bridges between different difficulty levels. A significant transformation that needs to be mastered is from textbooks written by experts for novices to specialised research papers. The former are often written to be appealing and action-oriented, while the latter are written to emphasise interpretation and understanding the significance of events (Biber & Conrad, 2019) (p. 132).

Ethnographic approach

In ethnographic research, the actions of people and the accounts they give are studied within the context of the everyday life they lead. The data obtained is analysed to provide interpretations of the meanings, functions, and consequences of the actions and practices that are observed (Hammersley, 2019)(Chapter 1). Critical aspects of the ethnographic approach are paying close attention to detail, being as impartial an observer as possible by taking into consideration the observer effect, being aware of the natural environment of a phenomenon, being sensitive to patterns and constructing interpretations. Such a mindset is not exclusive to the social and human sciences. The ethnographic approach builds theories and finds answers (Madden, 2017). In the process of analysis it is found that ethnography produces a characteristic ‘funnel’ structure where over time there is increasing focus during which concepts emerge and these are further developed into typologies and models that facilitate the construction of schemas and other mental structures.

The book Writing Analytically was chosen as a source because it had strong constructivist and discourse connections and because it contained numerous activities and exercises that could be easily adjusted to an engineering context even though it was written mainly to develop reading and writing skills in the humanities and social sciences. The text analysed in the book is primarily verbal, although the book includes analysis of images and pictures appearing, for example, in advertisements. The conceptual leap made in this paper is to expand the analytical framework focused on text to include multimodal text formats such as any symbolic representation and language, including mathematical expressions, computer code, engineering and scientific diagrams, figures, and drawings, movement patterns associated with machines, physical objects in general and combinations of the above.

Key elements in the analytic thinking approach are leveraging students' innate observational and pattern recognition skills, emphasising the importance of the details of the objects of study, and developing conscious awareness of judgment making and evaluation processes. Attention-to-detail tasks model the empirical approach used in ethnographic fieldwork and are designed to facilitate engagement with the raw substance of subject domain concepts, techniques and practices in their natural milieu while avoiding prejudgment and resisting vague generalisations. Such direct experiencing of the thingness of things (their composition, texture, shape etc.) allows meaning to emerge from acting upon concrete situations. (See, for example, (Emerson, Fretz, & Shaw, 2011) and (Blommaert & Jie, 2020) for book references on ethnographic fieldwork techniques.) This establishes a constructivist and interpretivist paradigm whereby students can engage in a conversation with the topic in which the "learner is actively involved in creating the structure through deep engagement with content", enabling the "inner logic of the subject and its pedagogy" to be revealed (Entwistle, 2009) (p. 97).

The approach developed is highly task-based, supporting engagement and the development of self-capacities. Scaffolding techniques, whereby supports are gradually removed, are used to reduce initial cognitive load and make interaction with subject material more manageable. Initially, tasks are designed to be easy to execute. These then progress to greater levels of sophistication and difficulty. Specific techniques incorporated in the exercises used in our approach for achieving these aims include:

- Having students write lists that are then ranked, with explanations given for ranking.
- Selecting extracts to analyse (sentences, paragraphs and passages) based on what students consider representative and significant.
- Iterative application of methods to build on what has already been discovered, with initial ideas modified and merged and new ideas created.
- Placing a strong emphasis on exploring assumptions, implications and interpretations.
- Analysing how choices, particularly by text authors, are made.
- Establishing a conversation with the content.

Bloom's taxonomy

Bloom's taxonomy is used as a reference frame to relate the ethnographic approach to understanding in the broader learning context. Bloom's taxonomy is a familiar device that specifies different levels at which learning occurs, and is widely used to develop course objectives, structure course material, devise assessment tasks and evaluate learning. The original taxonomy, developed in 1956 (Bloom, 1956), has six levels described by nouns: (1) knowledge, (2) comprehension, (3) application, (4) analysis, (5) synthesis, (6) evaluation. The revised taxonomy (Anderson & Krathwohl, 2001) has nouns replaced by verbs to emphasise the process aspects of learning; some levels have been renamed, and the top two levels are reversed: (1) remembering, (2) understanding, (3) applying, (4) analysing, (5) evaluating, (6) creating. (Cannon & Feinstein, 2005). Although learning occurs across all levels in Bloom's taxonomy, the comprehension/understanding level plays a pivotal role. "Students who demonstrate mastery of content at the comprehension level are more likely to be successful with learning at the application and analysis levels" (Verenna, Noble, Pearson, & Miller, 2018) with "comprehension form[ing] the center of the hierarchical representation with application, analysis, synthesis, and evaluation radiating from that center" (Stoker and Kropp, 1971). An important component of comprehension is interpretation where "learning occurs not by recording of information but by interpreting it" (Resnick, 2018). The ethnographic approach of moving from 'data' to interpretation facilitates this process. Exposure to higher level of learning occurs by requiring students to make evaluations and judgements when ranking items in a list and selecting passages for study.

Tasks and Exercises

This section describes the various tasks used in our approach. The tasks are based on of those given in (Rosenwasser & Stephen, 2019) (more details of tasks can be found in this reference). The order of description is approximately in the order of presentation to students.

Patterns: Detecting and explaining patterns and relationships is essential to understanding and is an easy but effective means to begin an exploration of a new text. The particular types of patterns considered are repetitions, strands and binaries. Repetitions are "words" and features that repeat exactly. Strands refer to sets of related words and phrases. Binaries are opposites in the text. Also included are anomalies that violate patterns or are unexpected. The task begins by reading a passage of text and making lists of repetitions, strands and binaries found. For strands, the connecting logic and semantics are recorded. The next step is to rank the items found. This can be conducted per pattern type or for the aggregated list (typically, the top three items are ranked). The final step is to explain why the items were ranked in the order chosen.

Notice and focus: The first step (notice) is to list observed details of the environment (the 'text') using an immersive approach. The emphasis is on neutral observation rather than making interpretations or asking questions such as "what do you like?" or "what do you think?". Typically, lists can be long, e.g., ten or more items. The next step is to focus on specific targets and record what attracts attention and what is interesting, revealing, significant, strange or odd. The tasks conclude by ranking items and providing the reasons for the rankings.

Paraphrase x3: Paraphrasing aims to unlock deeper meaning and bridge the gap to interpretation. This exercise requires students to take a short piece of text, usually no more than one or two sentences, that is considered representative or of significance in a text. Three paraphrases are produced with the emphasis on word-for-word paraphrasing. The focus on what the text is actually saying rather than describing overall impressions or the 'gist' of the text. Devising paraphrases in this way involves the manipulation of internal representations of relationships in the text. The task concludes by exploring what the three paraphrases may suggest or imply.

So what?: The "So what?" exercise continues the process of interpretation by taking a piece of text and asking "So what?" to discover its implications. The question asks, "If one thing is true, then what else is true?". Alternative ways of asking questions include: "And so?", "What do the observations mean?", "Why do they matter?", "Where do they get us?", "What do we gain and what do we lose?" Additional implications are found by "So what?" iteratively.

Reading with a lens: This exercise assists with "knowing where to look" (Blommaert & Jie, 2020). This allows texts to be studied from different perspectives, theoretical frameworks and contexts. Context can be regarded either as a macro-context, which defines broad contexts that are stable and predictable or as a micro-context, which is specific to a particular situation (Blommaert & Jie, 2020). Preparatory work may be included to become familiar with different lenses.

Reformulating binaries: In this exercise, the binaries obtained from the earlier analysis are re-examined to refine object categories and lines of argument. The activity uses questions such as: Has the binary been named adequately? Is another formulation more accurate? Is one side of the binary weighed more than the other side? Are both sides of a binary separate or parts of a single complex phenomenon? This is assisted by analysing critical terms in the binary, rephrasing and asking, "to what extent?".

The pitch, the complaint, the moment: As text length increases, argumentation strategies and awareness of genres become more critical. The segmentation of texts and moves between segments can be analysed by examining the pitch, the complaint and the moment. The pitch refers to what the piece wants you to believe/think: What set of circumstances is the text addressing? What caused the writer to say this? The complaint is what the pitch is reacting against. What was unacceptable? The moment where is the writer coming from: Why was this written at the time it was? What was the state of the world at that time? The emphasis in the exercise is on understanding the author's intentions rather than what the reader thinks they are.

Summarising: This task integrates different skills, attention-to-detail and interpretation. In essence, summarising is recounting someone else's ideas in reduced form in your own words, laying out its significant parts and contextualising accurately. Key questions to ask are: Which are ideas most significant? Why? How do ideas fit together? What do key passages actually mean? Students are asked to describe with care and choose words that convey precise meaning. Ineffectual summaries often are just lists with little connecting logic. This can be avoided by looking for underlying structure, avoiding general coverage by selecting information on an underlying principle, reducing the scope and asking what the writer is aiming to get the reader to think.

Application of the approach to an engineering unit

The analytic thinking exercises described in the previous sections were tested in an undergraduate third-year unit on random processes in a telecommunications engineering program. This unit covered fundamental probability models, random variables vectors and processes, statistical concepts, and spectral density. The multimodal text included significant amounts of mathematical notation and derivations (sometimes framed as formal theorems) with verbal explanations and diagrams (e.g., function graphs, Venn diagrams, etc.). The analytic thinking exercises complemented other forms of learning that included short lectures, interactive classes, problem-solving practicals, online quizzes and assignments. When a new analytic thinking exercise was introduced, it was by means of a short slide presentation that was reinforced immediately with brief, interactive activities in either small groups (3-4 students per group) and/or the entire class. Students then carried out tasks independently as part of a formal assignment.

Class-based exercises: Engagement during group-based exercises was positive, with students being animated and enjoying the experience. Listening to student talk (not recorded), the instructor noted the range of responses was broad and showed unexpectedness, originality and insight. The greatest benefits were obtained when students made an honest attempt rather than waiting for instructor responses.

Assignment questions on the analytic thinking approach were included in the first three of four assignments for the unit. The text extracts were selected to engage students with deeper and more advanced topics. Table 1 shows example assignment questions for those three assignments. The analytic thinking exercise question was worth 10% of the assignment mark in each case. Assignments were assessed not for the correctness of answers but on the proportion of completion. Sample answers and explanations were provided following the assignment return.

The extract used and the sample response for the Assignment 1 questions on detecting patterns is shown in Appendix A (however, due to space limitations, student responses are not shown). This assignment was the first independent attempt students had to use the analytic thinking techniques. The text extract was from a graduate textbook on formal theories for defining families of probability events (using π-systems), which is part of the fundamental conceptual underpinnings of probability. This theory is the product of communities of researchers, and by examining low-level details, students obtained insight into the struggles faced in developing these theories. A range of responses was provided with varying levels of sophistication and depth. The widest variety of responses was in the ranking of items and the reasons for the ranking. Assignment 2 used paraphrase x3 to improve understanding of the significant concept that uncorrelated random variables need not be independent. This concept is often not studied in detail in undergraduate courses. Students were required to follow the line of argument, calling upon their knowledge of

Assignment 1: Following is an extract from a book on how to define events occurring in probability. Apply the analytic thinking method to do the following. • Determine what repetitions, strands and binaries are in the extract. • After combining all the repetitions, strands and binaries, how would you rank them? • Explain why you ranked these items in the order you chose. • Briefly explain what this example is aiming to show.
Assignment 2: Following is an extract from a book on an example of random variables that are uncorrelated but are not independent. Apply the analytic thinking method to do the following. • Determine what repetitions, strands and binaries are in the extract. • Rank the list obtained and explain why you ranked these items in the order you chose. • Find a representative sentence in the extract that captures the essence of the example. Use the paraphrase x3 method to obtain three paraphrases of the representative example. Following this, provide an interpretation of the relevant sentence. • Briefly explain how this example proves that two random variables are uncorrelated but not independent.
Assignment 3: Following is an extract from a book on tracking, estimation and linear least squares. a) Write a summary of the main results in the extract. b) Identify in the extract important parts of the theory that have been covered in the unit. c) Provide the missing steps to obtain the solution of equations (7.1) and (7.2). d) Verify the equations for the first example on the last page.

Table 1: Assignment questions using the analytic thinking method

various probability and mathematical concepts such as densities, independence, correlation, and calculus. Part of the difficulty was that the explanation in the extract was brief, and argument connections were not always apparent (which is typical of such descriptions). The paraphrase x3 technique assisted with finding conceptual relations to facilitate understanding of the more intuitive mathematical ideas involved. Student responses showed that those selecting richer passages for analysis produced a deeper understanding. Assignment 3 was on the use of least-squares estimation for tracking (four-page extract). It began by requiring a summary of a text to be written using the analytic thinking approach. This was followed by an analysis of how the text was linked to broader theory and a detailed study of two critical equations in the text.

The *final examination* consisted of a take-home set of questions. Analysis of the results of this examination provided a means of assessing the benefit of using the analytic approach. Qualitative evaluation of answers, based on accumulated instructor experience over multiple offerings of the unit, showed improved learning outcomes compared to previous offerings of the unit when the approach was not used. Answers were more detailed and precise with students demonstrating better ability at solving complex problems and thinking their way around obstacles in novel situations to come up with alternative solutions.

Survey: Evaluation of the approach's effectiveness from a student's perspective was obtained from an online class survey conducted in the fifth week of the semester. The purpose of the survey was to obtain feedback on various teaching methods being used and make adjustments if necessary. The survey ratings showed that the analytic thinking exercises scored well (4.2/5) compared to other high rating activities such as class exercises (4.5/5) and example problems (4.5/5). Although the sample size was small (the class size was 13, and the number of survey responses was 6), and the results were not statistically significant, the survey results and the level of engagement suggest that the approach was considered worthwhile by students.

Discussion

The analytic thinking approach was deployed as a sequence of tasks that increasingly shifted students from observation to interpretation. Thinking became more individual, refined and sophisticated as students progressed and engaged in a dialogue with the topic. Using a staged approach had the benefit of being relatively easy and manageable for students to do. For example, in the detecting patterns and notice and focus exercises, the initial list building is conducted without too many distracting tasks. The ranking and explanation steps are then done immediately following when the list information is still fresh. The paraphrase x3 and "So what?" exercises allow further inclusion of theoretical knowledge into schemas and mental models through interpretation and consideration of assumptions and implications. It was found that the method works best for short texts because of the amount of detail that needs to be considered. For a middle level undergraduate technical unit one to four pages of text was an acceptable length, depending on the task. The ethnographic approach enables a broad range of cognitive comprehension capacities to be developed, including focussed attention, retrieval of semantic knowledge, making evaluations and judgements, adding precision in thinking, following lines of argument, discovering relationships, building mental models, inductive and abductive thinking and theorising. The approach allows more advanced material to be included in the curriculum that broadens the intellectual base of knowledge taught and makes students more aware of the social constructivist aspect of knowledge creation. The interactive exercises improve engagement by adding an extra dimension and variety to classes. Lifelong learning is supported by the development of new mindsets, increased awareness of self-capacities, improved metacognition and having available practical yet general content analysis strategies via the task exercises. The creative aspect of learning is developed when students are required to express ideas in their own words. The techniques developed augment the arsenal of active learning approaches that are available to instructors. Paying attention to detail also aligns with the development of rigor in the 4Rs post-modernist curriculum development theory of (Doll Jr, 1993). Although one of the goals of the work was to enhance the self-learning capacities of students, how many of the techniques used in this unit students will use in future units could not be assessed. However, it is hoped that positive dispositions such as paying attention to detail and engaging in a conversation with content will continue. For instructors, the use of the approach promotes "bridg[ing] the gap between what we know about learning and how we design and teach courses" (Ambrose, Bridges, DiPietro, Lovett, & Norman, 2010). By observing student responses, staff learn "about how learning works".

Conclusion

The paper showed how generalising the notation of text representation enabled the use of ethnographic principles to promote the understanding of complex texts and learning the "inner logic" of subjects. The results suggest that the approach can be a valuable complement to other forms of teaching. Through a series of simple exercises that can be used across general subject domains, understanding complex and advanced material can be improved. The focus of this paper has been on analysis for understanding. However, ethnographic principles can also be used to develop skills for writing and the creation of new ideas and knowledge. These activities invoke more of the upper levels of Bloom's taxonomy. Many of the tasks described above can assist with the creative aspects of learning. Additional tasks described in (Rosenwasser & Stephen, 2019) can be used and adapted to promote such 'writing' (in the general sense, e.g., mathematical creativity). We refer readers to (Rosenwasser & Stephen, 2019), due to space limitations.

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Copyright statement

Appendix

Extract:

Definition. A family $\mathcal{I}$ of subsets of Ω is called a **π-system**, if $\mathcal{I}$ is closed under intersections: if A, B are in $\mathcal{I}$, then $A \cap B$ is in $\mathcal{I}$. A σ-additive map from a π-system $\mathcal{I}$ to $[0, \infty)$ is called a **measure**.

Example. 1) The family $\mathcal{I} = \{\emptyset, \{1\}, \{2\}, \{3\}, \{1,2\}, \{2,3\}, \Omega\}$ is a π-system on $\Omega = \{1,2,3\}$.
2) The set $\mathcal{I} = \{[a,b) \mid 0 \le a < b \le 1\} \cup \{\emptyset\}$ of all half closed intervals is a π-system on $\Omega = [0,1]$ because the intersection of two such intervals $[a,b)$ and $[c,d)$ is either empty or again such an interval $[c,b)$.

Definition. We use the notation $A_n \nearrow A$ if $A_n \subset A_{n+1}$ and $\bigcup_n A_n = A$. Let Ω be a set. $(\Omega, \mathcal{D})$ is called a **Dynkin system** if $\mathcal{D}$ is a set of subsets of Ω satisfying

(i) $\Omega \in \mathcal{A}$,
(ii) $A, B \in \mathcal{D}, A \subset B \Rightarrow B \setminus A \in \mathcal{D}$.
(iii) $A_n \in \mathcal{D}, A_n \nearrow A \Rightarrow A \in \mathcal{D}$

Lemma 2.1.2. $(\Omega, \mathcal{A})$ is a σ-algebra if and only if it is a π-system and a Dynkin system.

Proof. If $\mathcal{A}$ is a σ-algebra, then it certainly is both a π-system and a Dynkin system. Assume now, $\mathcal{A}$ is both a π-system and a Dynkin system. Given $A, B \in \mathcal{A}$. The Dynkin property implies that $A^c = \Omega \setminus A, B^c = \Omega \setminus B$ are in $\mathcal{A}$ and by the π-system property also $A \cup B = \Omega \setminus (A^c \cap B^c) \in \mathcal{A}$. Given a sequence $A_n \in \mathcal{A}$. Define $B_n = \bigcup_{k=1}^n A_k \in \mathcal{A}$ and $A = \bigcup_n A_n$. Then

$A_n \nearrow A$ and by the Dynkin property $A \in \mathcal{A}$. Also $\bigcap_n A_n = \Omega \setminus \bigcup_n A_n^c \in \mathcal{A}$ so that $\mathcal{A}$ is a σ-algebra. □

Sample response:

Repetitions: π-system, family, subset, Ω, Dynkin system, , Ω\A, ∩, ∪, ∈, subset, interval, set, An, property, ↑
Strands: set operation (∩, ∪,), intersection; set of subsets, family; map measure
Binaries: union/intersection; set/member of set; Ω (sample space)/subset; n (current member) (n=1) next member
Rank: 1. An ↑ A 2. I is closed under intersections 3. Interval [a,b)
Reason for ranking
1. It is most important since it shows that limits of sets are in the sigma algebra.
2. The closure is important in that the operation preserves the property.
3. Intervals are a good example of families of a subset.

Explanation The example shows that events on the real line can be constructed from simple sets such as intervals.