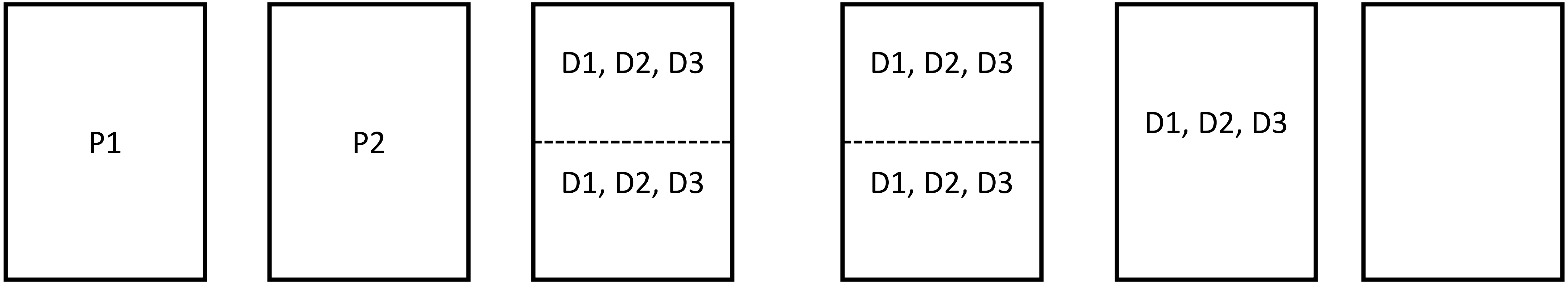
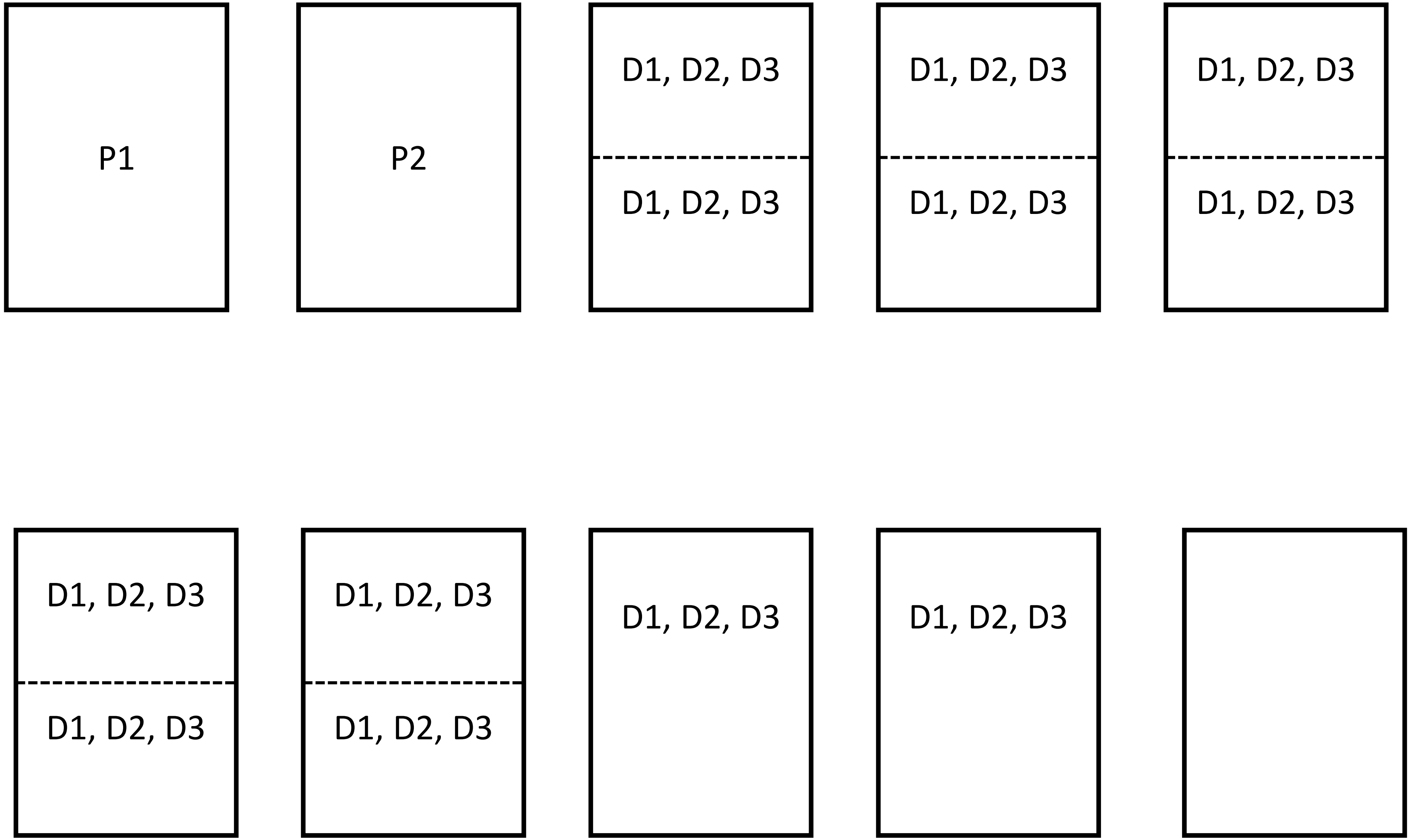
Developing the research D1, D2 and D3



Bibliography – D1

Summary of skills/knowledge developed – D3

	Planning	Development
A	P1 Thorough consideration and refinement of a research question. P2 Thorough planning of research processes that are highly appropriate to the research question.	D1 Thorough and highly resourceful development of the research. D2 In-depth analysis of information and exploration of ideas to develop the research. D3 Highly effective development of knowledge and skills specific to the research question.



Bibliography (all sources you have looked at) = D1
Summary of skills and knowledge developed = D3

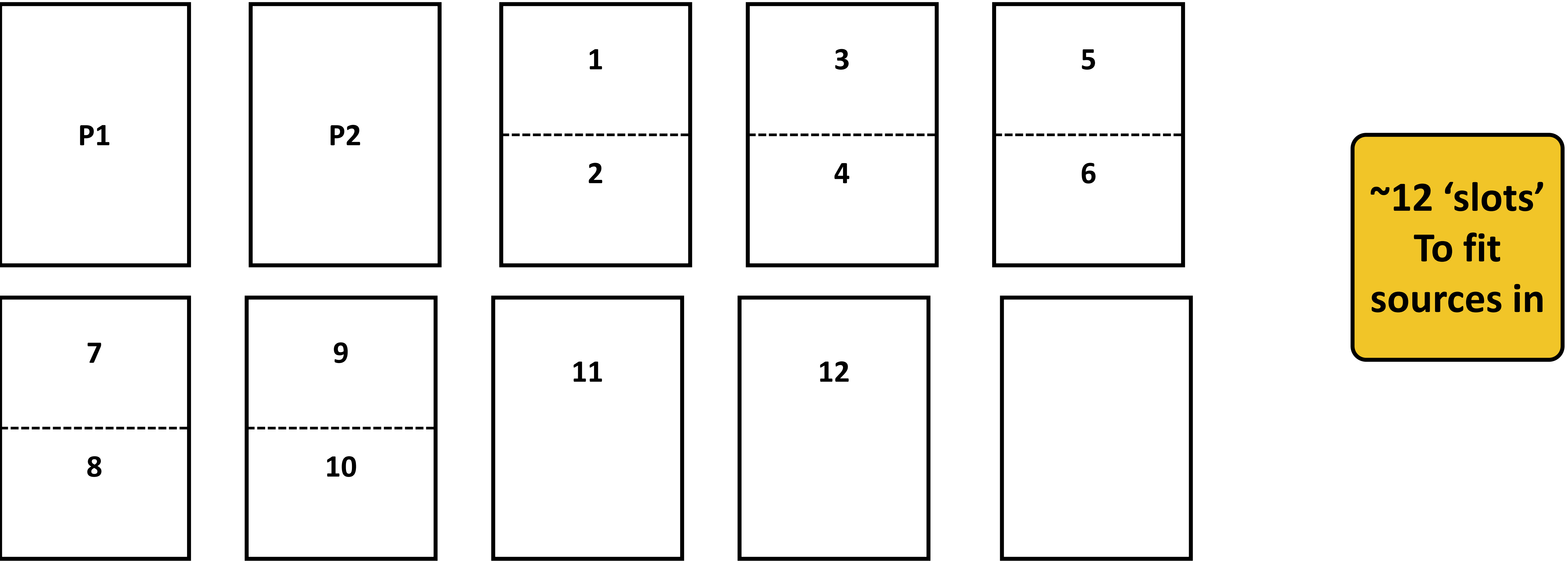
Websites

Journal Articles

Videos

Primary Research

Websites	**35**
Journal Articles	**15**
Videos	**8**
Primary Research	**1**

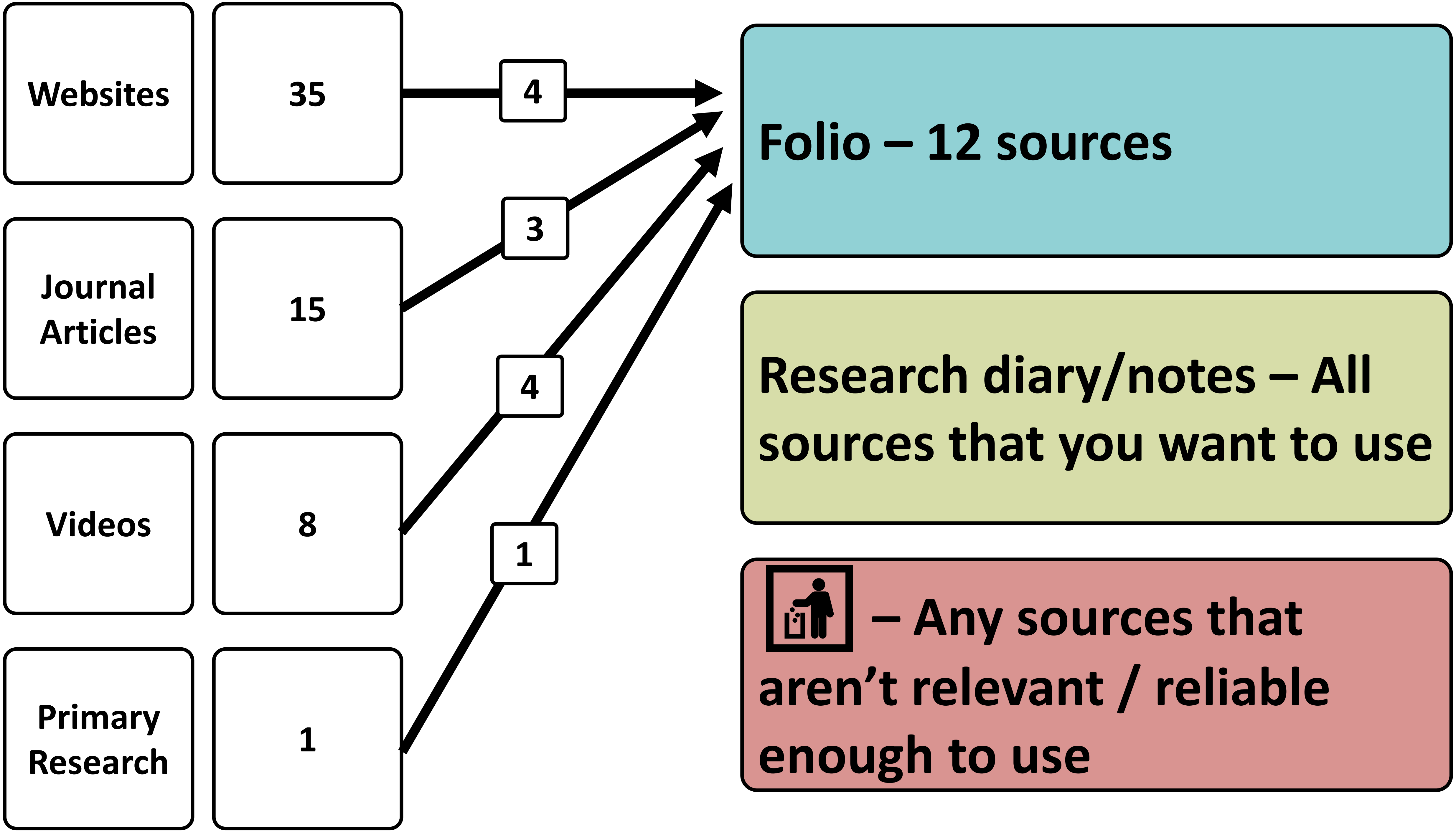

P1
P2
1
2
3
4
5
6
7
8
9
10
11
12
~12 ‘slots’
To fit
sources in

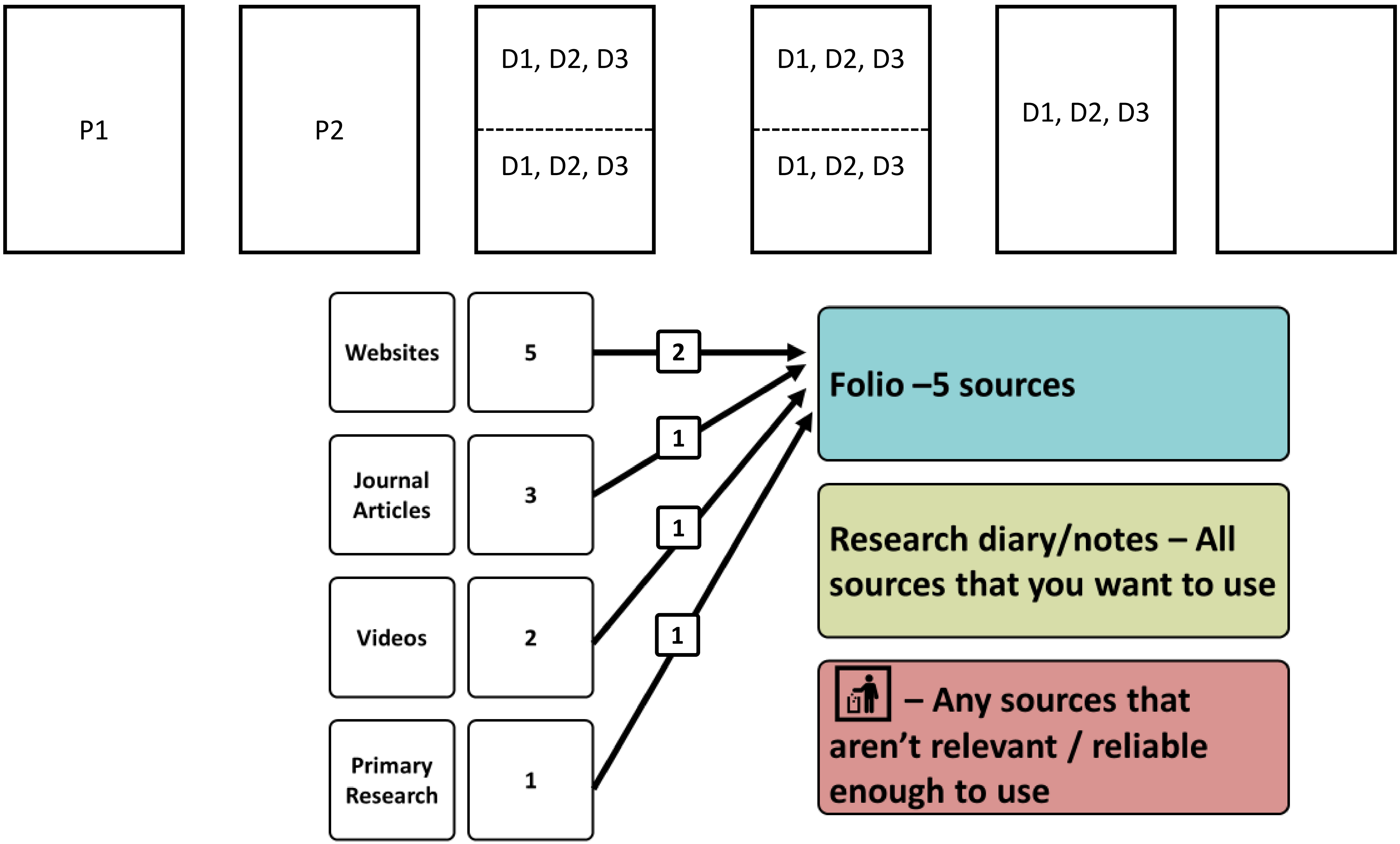
Websites	35
Journal Articles	15
Videos	8
Primary Research	1

Folio – 12 sources

Research diary/notes – All sources that you want to use

– Any sources that aren’t relevant / reliable enough to use


Websites
35
4
Journal Articles
15
3
Videos
8
4
Primary Research
1
1
Folio – 12 sources
Research diary/notes – All sources that you want to use
– Any sources that aren't relevant / reliable enough to use


P1
P2
D1, D2, D3
D1, D2, D3
D1, D2, D3
D1, D2, D3
D1, D2, D3
Websites
5
2
Journal Articles
3
1
Videos
2
1
Primary Research
1
1
Folio –5 sources
Research diary/notes – All sources that you want to use
– Any sources that aren’t relevant / reliable enough to use

D1

-Do the things you planned to do in P2

-Record key findings (you won’t fit them all in the folio)

-Bibliography can help with this (but not much)

-Having a summary of each topic is a good idea

Development	
D1	Thorough and highly resourceful development of the research.
D2	In-depth analysis of information and exploration of ideas to develop the research.
D3	Highly effective development of knowledge and skills specific to the research question.

D1

Finding, reading , and highlighting source

Para on key findings

Suzuki.W. (2018), The brain-changing benefits of exercise, https://www.ted.com/talks/wendy_suzuki_the_brain_changing_benefits_of_exercise, Accessed 15th November 2018

Noes on video:

Prefrontal cortex:
- Critical for focus and attention

Temporal lobe:
- Contains the hippocampus

- A memory is formed by neurons having a brief moment of electrical activity between eachother

Primary source area:
- She found that after she went to the gym, she was able to focus and maintain her attention on a mundane task longer than she had before.
- Her long-term memory also seemed to improve to her, she could remember a lot more of what she was studying in her lab.
- Literature all pointed out the exercise provides: better mood, better energy, better memory, better attention

How exercise transforms the brain immediately:
- It has an immediate effect because exercise immediately increases levels of neurotransmitters like dopamine, serotonin and noradrenaline.
- The increase in these chemicals improves mood.
- Exercise can increase the ability to shift and focus your attention and the improvement will last for up to two hours.
- It also improves reaction times

The long-term effects of exercise:
- An increase in cardiorespiratory function enables long-term affects to happen
- "Exercise actually changes the brain's anatomy, physiology and function." Wendy Suzuki
- Exercise enables the production of new brain cells in the hippocampus, which in turn leads to an increase in volume, which in turn improves long-term memory.
- Exercise improves attention dependent on your prefrontal cortex.
- Good mood neurotransmitters increase and sustain for long-term improvements.

The protective effects:
- Exercise gives the brain protective effects.
- The hippocampus and prefrontal cortex are two areas most susceptible to neurogenerative diseases and exercise gives a form of protection to this.

Length:
- 3 to 4 times a week of 30 minute sessions

Source details:5 TEDwomen, 2017, The brain-changing benefits of exercise, Available at: https://www.ted.com/talks/wendy_suzuki_the_brain_changing_benefits_of_exercise, Accessed 15th November 2018

Reliability:5 This source and the information contained in it are highly reliable because the author of the source is a professor of neuroscience and psychology at New York University. Also, the source is primary because she personally conducted the studies, meaning that the data can be trusted. The information is extremely current published on a credible website, all evidencing reliable material

Validity:5 This source is greatly valid to my research question because it discusses how the brain changes in anatomy, physiology and function in response to exercise and this includes memory and concentration. However, this source particularly focuses on memory and how changes in the brain's hippocampus structure and improve long-term memory.

Key findings:5 The main key findings from this source was the primary information which the neuroscientist gathered from observing herself in response to exercise. After a session in the gym, she felt more focussed and able to maintain her attention on a mundane task longer than she had previously. Furthermore, her long-term memory improved because she could remember information better. Also, from this source I noted that the increase in volume of the hippocampus is due to exercise enabling the production of new brain cells in the hippocampus, increasing the volume and improving long-term memory.

Leads:5 Leads are abundant from this source because it gives a brief overview of everything that exercise does to the brain, meaning that there are many paths to explore from the information gathered. One of these is the individual factors that lead to a change in the brain's anatomy, physiology and function in a beneficial way.

Conclusion on source:5 This source is a tremendously useful source, with trusted, reliable information and a great overview of changes that occur during and after exercise. This material will be used as foundation knowledge as I got into more detail about the changes

Development of capabilities:5 The literacy capability was developed because I had to improve my note-taking skills whilst watching a video. This also developed the critical and creating thinking capability because I had to understand, evaluate and synthesise the information before taking notes.

D2

-Analysing the sources you put in the folio

Credibility: Can you trust the author?

Reliability: Is the source well made and seems to be true

Relevance: Will the source help you answer all your question or just one part?

Development	
D1	Thorough and highly resourceful development of the research.
D2	In-depth analysis of information and exploration of ideas to develop the research.
D3	Highly effective development of knowledge and skills specific to the research question.

D2

Analysis of reliability and validity

Suzuki W. (2018), The brain-changing benefits of exercise, https://www.ted.com/talks/wendy_suzuki_the_brain_changing_benefits_of_exercise, Accessed 15th November 2018

Noes on video:

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Leads:5 Leads are abundant from this source because it gives a brief overview of everything that exercise does to the brain, meaning that there are many paths to explore from the information gathered. One of these is the individual factors that lead to a change in the brain's anatomy, physiology and function in a beneficial way.

Conclusion on usefulness

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Development of capabilities:5 The literacy capability was developed because I had to improve my note-taking skills whilst watching a video. This also developed the critical and creating thinking capability because I had to understand, evaluate and synthesise the information before taking notes.

D3

-What **skills** did you develop in doing each process? (creating an experiment, highlighting and organising information)

-How did your **knowledge** specific to your question develop?

-You won't do both of these in every source

Development	
D1	Thorough and highly resourceful development of the research.
D2	In-depth analysis of information and exploration of ideas to develop the research.
D3	Highly effective development of knowledge and skills specific to the research question.

D3

How this source will lead to finding new knowledge

Conclusion on usefulness (includes how their knowledge developed)

Suzuki W, (2018), The brain-changing benefits of exercise, https://www.ted.com/talks/wendy_suzuki_the_brain_changing_benefits_of_exercise, Accessed 15th November 2018

Noes on video:

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Development of capabilities:5 The literacy capability was developed because I had to improve my note-taking skills whilst watching a video. This also developed the critical and creating thinking capability because I had to understand, evaluate and synthesise the information before taking notes.

CAPABILITIES AND SKILLS DEVELOPED:

I developed my personal and social skill while sourcing this article because I had to reach out to my surgeon and ask him to fill in this survey. This also meant that I had to phrase my questions formally to show that I had a basic understanding and wanted more in-depth information about my topic.

It was difficult for me to organise a face to face interview with him but that is what I wanted because then if I didn't fully understand something he said, I could ask him about it straight away rather than having to email him back.

I also developed my literacy skill because I wanted the surgeon to know that I had a deep knowledge on the subject through the way that I phrased my questions. This would also allow him to talk about the subject in-depth knowing that I would be able to understand what he was actually talking about. This meant that I had to research in-depth treatments, with the proper phraseology.

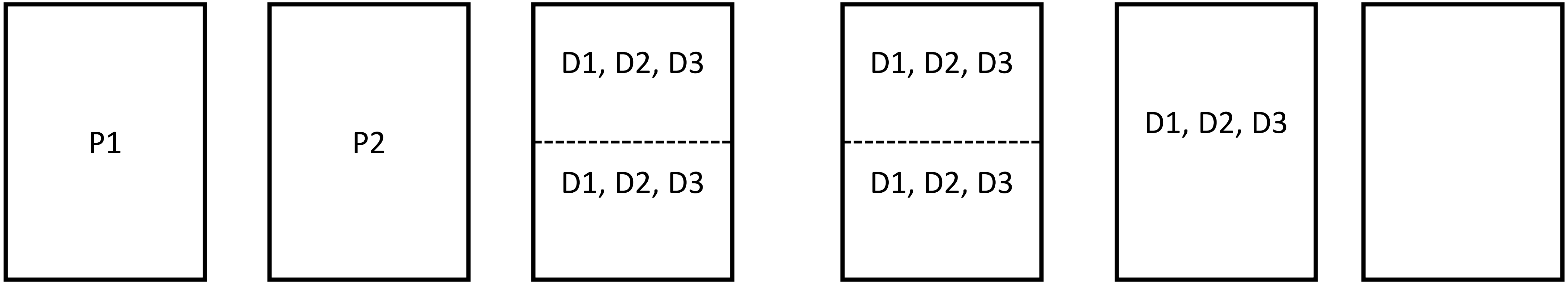
SOURCE TYPE - INTERVIEW WITH SURGEON

Don’t do D4

Development	
D1	Thorough and highly resourceful development of the research.
D2	In-depth analysis of information and exploration of ideas to develop the research.
D3	Highly effective development of knowledge and skills specific to the research question.
D4	Thorough [illegible] d understand[illegible] velopment of one or mor[illegible] es.

NO!

What to Do On The Last Page?



Bibliography – D1

Summary of skills/knowledge developed – D3

Things You Can Do On The Last Page

Bibliography – a list of **all** the sources you have found so far and their refence information

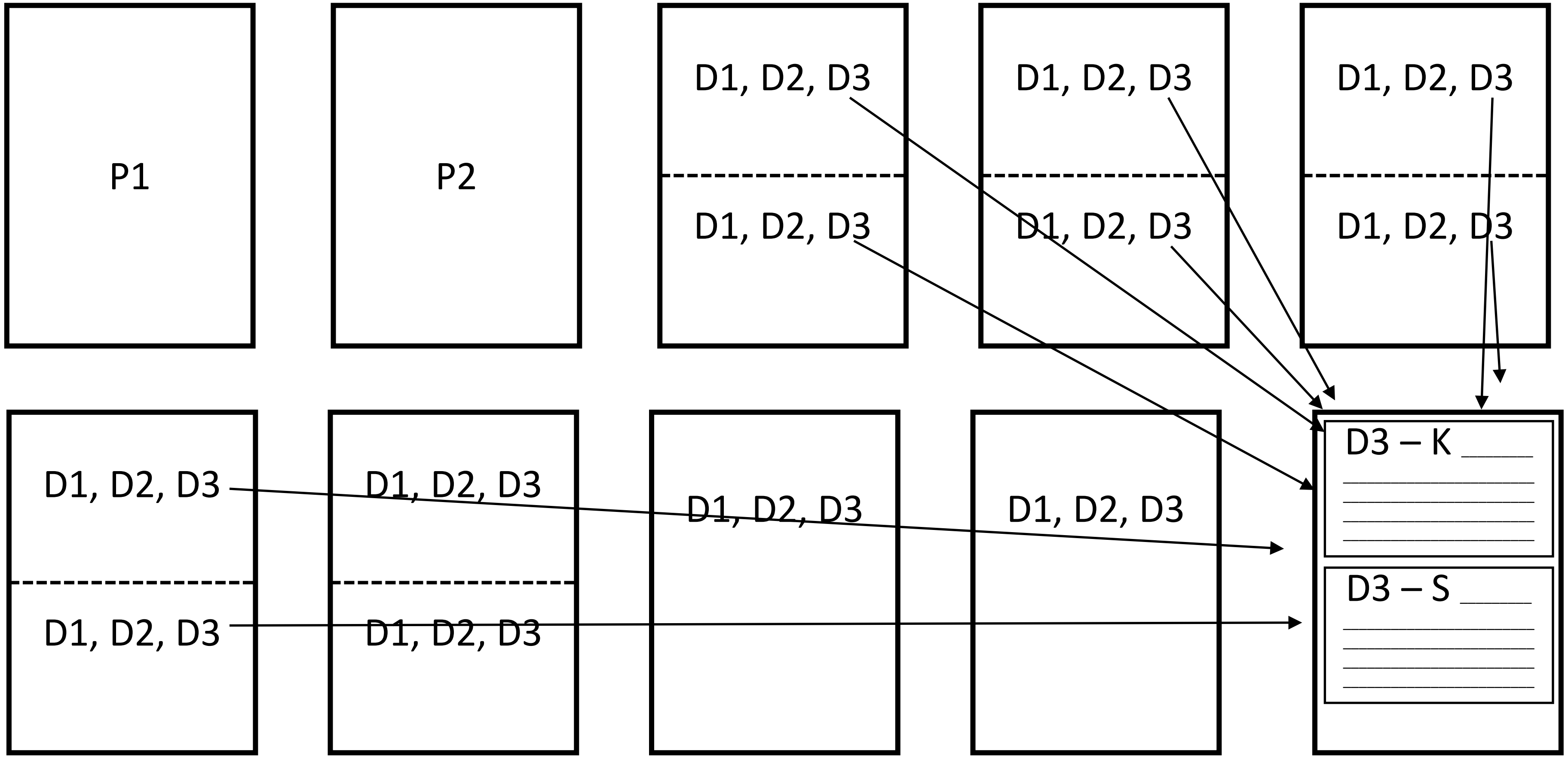
How this helps – this can be evidence for D1 as it shows you found many sources. However D1 is usually easy to prove from the sources you have already found so doesn’t add much to your mark for the amount of room it takes up.

Things You Can Do On The Last Page

Summary of Knowledge and Skills – This can be done as one paragraph, but it is better to have a paragraph on knowledge and one on skills.

How this helps – this allows you to summarise all the ways your knowledge and skills have progressed as you completed the folio. This will give a lot of evidence for D3.

Things You Can Do On The Last Page

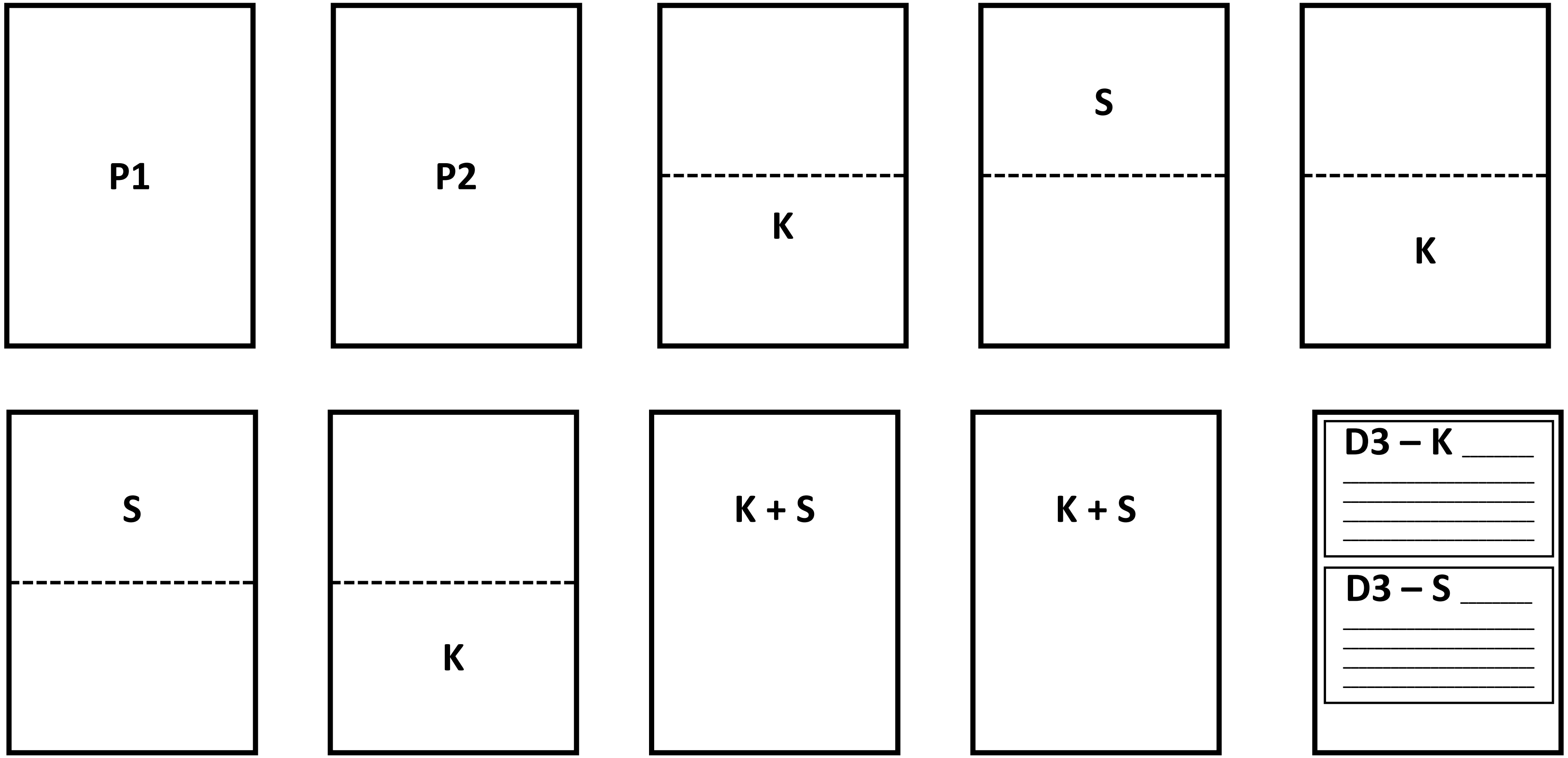


IMPORTANT

You probably won't do knowledge and skills in every single source.

Some will have a bit on knowledge development, some will have skills, some will have neither.

Things You Can Do On The Last Page



IMPORTANT

You probably won't do knowledge and skills in every single source.

Some will have a bit on knowledge development, some will have skills, some will have neither.

Reference List or Bibliography?

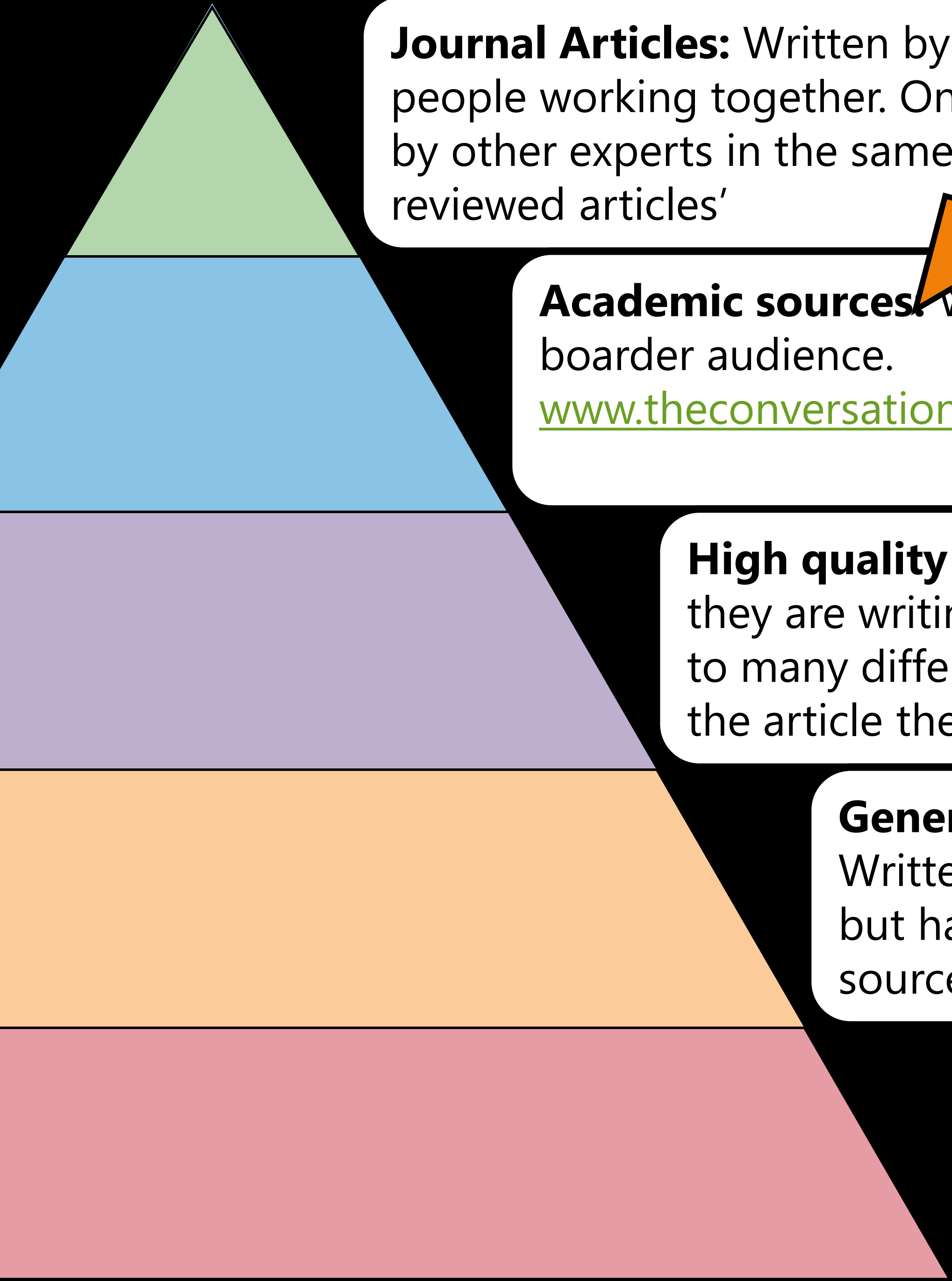
Reference List

- Lists all the sources that you **referenced**. If you didn't use it in the document it shouldn't be on the list.

Bibliography

- List of all sources that you looked at whether you refer to them or not.

Journal Articles Etc.



Journal Articles: Written by people who are experts in their area. Often written by teams of people working together. One article could be the results of years of research. Articles are checked by other experts in the same field before they can be published, so they are often called 'peer reviewed articles'

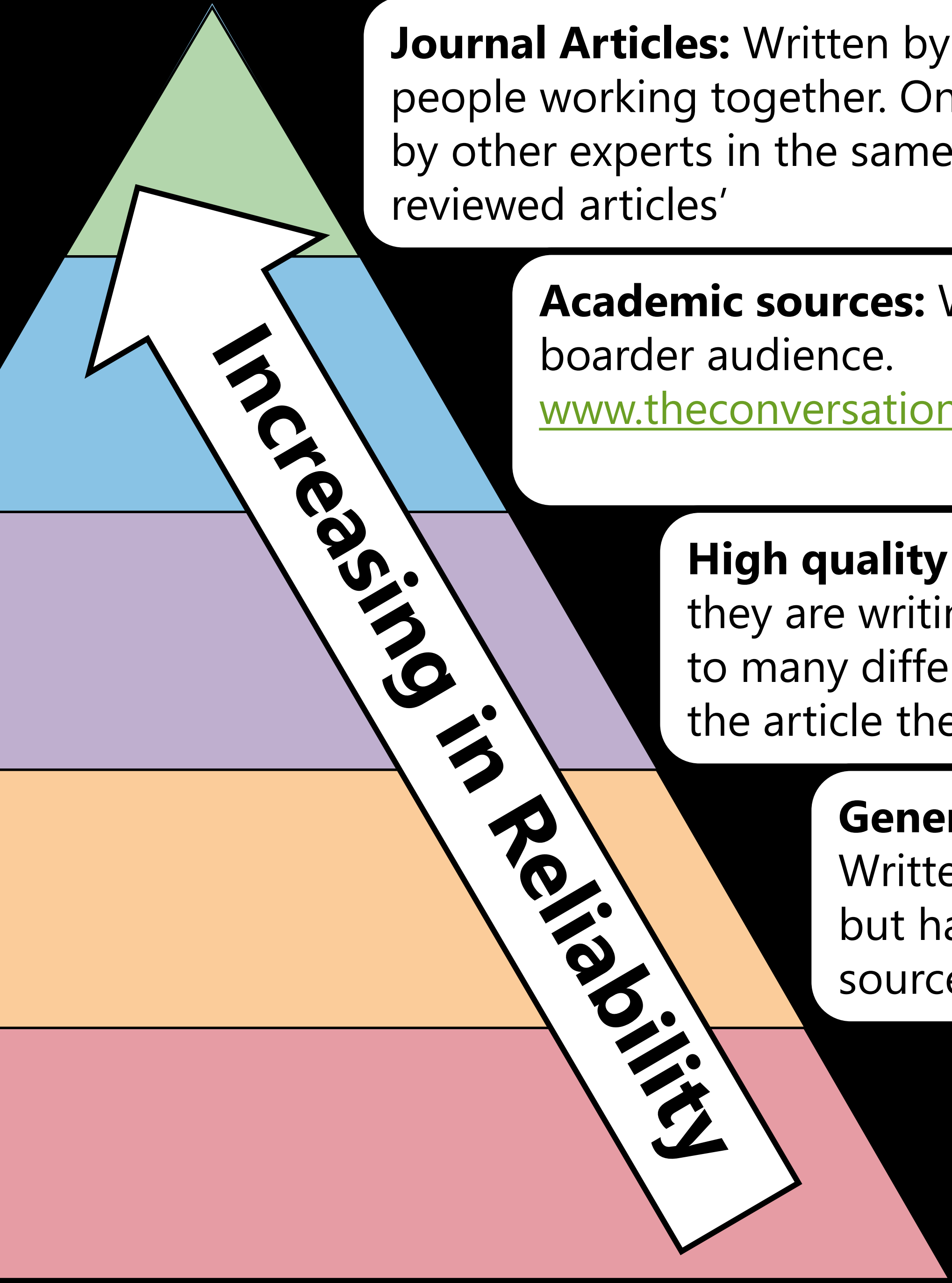
Academic sources: W n by experts in their field. Written to explain a relevant topic to a boarder audience.
www.theconversation.co

High quality non-ac ic: Written by people who are not experts in the field they are writing about re experts at research (a.k.a journalists). They would talk to many different people do a lot of their own research before putting together the article they are writing e news website articles are at this level.

General websites:
Written by people who a they are writing about but have done some rese and some 'low quality' sources may be this level a ten a subject expert).

Note: These sources could link to or refer to more reliable sources

The Rest: Made by people who are not experts and don't know how to research. Often quite obviously unreliable due to spelling errors, factual errors and other issues.
Tweets, Facebook posts, Blogs, YouTube videos



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www.theconversation.com

High quality non-academic: Written by people who are not experts in the field they are writing about but are experts at research (a.k.a journalists). They would talk to many different people and do a lot of their own research before putting together the article they are writing. Some news website articles are at this level.

General websites:

Written by people who are not experts in the area they are writing about but have done some research. Most news articles and some 'low quality' sources may be this level as well (or higher if written a subject expert).

The Rest: Made by people who are not experts and don't know how to research. Often quite obviously unreliable due to spelling errors, factual errors and other issues.

Tweets, Facebook posts, Blogs, YouTube videos

Primary research

- Is an expert (masters or PHD) in their area of study
- Conducts their own research. This research is then checked by other experts in that field and then written up and published in a journal.

Experts, lived experience and journalists

- Is an expert in their area of study
- Have experienced the thing you have studied
- Are experts at finding information and checking that it is correct

Opinion and secondary research

- Not experts
- Have read some information about the topic
- Base their opinions on other people’s info

1. **ABSTRACT** Provides an overall summary of the article
2. **INTRODUCTION** Introduces the research area, reviews past literature and overviews the current study outlined in article
3. **METHOD** Describes the who, what, when, where and how of the current study outlined in article
4. **RESULTS** Outlines and analyses the data
5. **DISCUSSION/CONCLUSIONS** Summarises the main findings of the current study and their importance. Identifies limitations and future research directions
6. **REFERENCES** List of the scholarly sources cited as evidence throughout the journal article

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International Journal of
Educational Research 35 (2001) 463–482

International Journal of
Educational Research

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Chapter 2

Learning about and learning from expert teachers

David C. Berliner

College of Education, Arizona State University, Tempe, AZ 85287, USA

Abstract

Studies of expertise in teaching have been informative, despite problems. One problem is determining the relative roles of talent vs. deliberate practice in the acquisition of expertise. When studying teachers, however, a third factor must be considered, that of context. The working conditions of teachers exert a powerful influence on the development of expertise. A second problem is that of definition because expertise in teaching takes different forms in different cultures, and its characteristics change by decade. A distinction is drawn between the good teacher and the successful teacher, characteristics of expertise that are often confused. A prototypical model of expertise is described and found to identify teachers who were both good and successful. Discussed also is the importance of understanding adaptive or fluid expertise, automaticity and flexibility. Finally, the development of teacher expertise is seen as an increase in agency over time. © 2002 Elsevier Science Ltd. All rights reserved.

Generalizing from studies of expertise in pedagogy and other fields should have been difficult because the research methods are almost always qualitative, focussed intensively on small numbers of individuals who are themselves highly unique. Nevertheless, in a relatively short period of time research on expertise in pedagogy and in other fields has proven to be both cumulative and informative.

According to Glaser (1987, 1990), about two dozen propositions about expertise are defensible. Paraphrased and abbreviated, some of these propositions are:

- Expertise is specific to a domain, developed over hundreds and thousands of hours and continues to develop;
- Development of expertise is not linear. Non-monotonicities and plateaus occur, indicating shifts in understanding and stabilization of automaticity;
- Expert knowledge is structured better for use in performances than is novice knowledge;

E-mail address: berliner@asu.edu (D.C. Berliner).

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PII: S0883-0355(02)00004-6

- Experts represent problems in qualitatively different ways than do novices. Their representations are deeper and richer;
- Experts recognize meaningful patterns faster than novices;
- Experts are more flexible, are more opportunistic planners, can change representations faster when it is appropriate to do so. Novices are more rigid in their conceptions;
- Experts impose meaning on ambiguous stimuli. They are much more "top down processors." Novices are misled by ambiguity and are more likely to be "bottom up" processors;
- Experts may start to solve a problem slower than a novice, but overall they are faster problem solvers;
- Experts are usually more constrained by task requirements and the social constraints of a situation than are novices;
- Experts develop automaticity in their behavior to allow conscious processing of more complex information; and,
- Experts have developed self-regulatory processes as they engage in their activities.

These propositions are derived from scores of studies of expertise in different fields of endeavor, from chess and taxi driving, to radiology and physics problem solving. Berliner (1994a, b) asserted that this particular sub-set of propositions is supported also by the research on expert teachers. A similar set of propositions is provided by Bransford, Brown, and Cocking (1999). The similarity in propositions derived from studies of expertise, across fields of endeavor, attests to the robustness of this research program. The research provides an interesting case in the social sciences, namely, one in which many imperfect studies, across many different kinds of activities, yield a coherent body of knowledge and heuristic theory. However, despite the cumulative nature of the research, investigations in this field have been hampered by two major problems.

1. Research problems

One of the problems for the field is the argument over the role of talent in the development of expertise. Talent may be thought of as individual differences in abilities and skills that seem like gifts or innate capacities, and seem to be "hard-wired" into individuals. The question that needs to be answered is how, and in what ways, does talent influence the development of expertise in domains like music, wrestling or reading?

A second problem for scholars is the lack of objective criteria in certain fields for the identification of experts. Expert political scientists, taxi drivers, and teachers are harder to find than, say, expert bridge players or physicists. The latter are regularly judged through tournaments and Nobel prize competitions, informing us who is "expert".

1.1. Talent, expertise, context, and pedagogy

The debate about the role of talent is whether talent is the driver behind the will to achieve at high levels, or whether the acquisition of expertise is almost entirely a function of motivation to practice and learn from that experience, *independent* of initial talent. Ericsson and Charness (1994) have taken the strong environmental position. They claim it is motivation and interest that give rise to expertise, and no persuasive evidence exists that specific talent or biological inheritance is a prerequisite for acquisition of expert levels of performance. Expertise, they say, is a result of extended training that "alters the cognitive and physiological processes of experts to a greater degree than is commonly believed possible" (p. 726). On the other hand, using expertise in music and art as examples, and contrasting expertise in these areas to those that require more drill-like activities such as ice-skating and typing, Gardner (1995) argued that talent, not mere practice, cannot be overlooked. In another artistic domain, acting, Noice and Noice (1997) argued that no amount of practice can move someone to the top level. Talent, however ambiguous the term, is required. Actually, Gardner never refuted the importance of deliberate practice in the acquisition of expert performance. Rather he believed that more than simple interest brings a person to strive for a high level of achievement in music, art or athletics. Talent has a major role to play, according to Gardner, both in the development of that interest and in determining the final level of accomplishment attained by a developing expert. Winner (1996) and Sternberg (1996) also refuted the Ericsson and Charness (1994) and Ericsson (1996) claim that expertise can be predicted more from the quantity and quality of practice then it can be from the vague and romantic concept of "talent."

This debate is important but of little practical interest to those who study pedagogical expertise. The fact is that "talent" for teaching is probably an extremely complicated interaction of many human characteristics. These might include sociability, persuasiveness, trustworthiness, nurturent style, ability to provide logical and coherent stories and explanations, ability to do more than one thing at a time, physical stamina, the chance to "play teacher" with a younger sibling or playmate, and so forth. The "talents" or background characteristics for those who enter the teaching field *as adults* are likely to be both biological and socially determined, and the interactions among these are probably well beyond our ability to catalog. Regardless of the talents, proclivities, and opportunities that motivate one to become a teacher as an adult, extensive deliberate practice is still needed to become highly accomplished in teaching, as it is needed to become accomplished in other complex activities like playing the violin, medical diagnosis, or creating pottery.

There is still another reason not to be concerned about talent. Arguments about the primacy of practice over ability or ability over practice may be secondary when studying a field like teaching. Overlooked is the power of context. McLaughlin and Talbert (1993), Cohen (2000), and others have made the case that teachers will reach differential levels of productivity depending on the workplace conditions of the site at which they find themselves. Policies from the principals, superintendents, and school board, along with the expectations of the community, determine the

organization of a school and its climate. These policies subtly, but powerfully affect teachers' attitudes, beliefs, enthusiasm, sense of efficacy, conception of their responsibilities, and teaching practices. We too often think of expertise as a characteristic of a person, when psychology has repeatedly taught us that such characteristics are typically an interaction of the person and the environment in which they find themselves (Rich, 1993).

Thus, context has to be thought of as a third variable and probably of equal status with talent and practice in the debate over important influences in the development of accomplished, exemplary, or expert teachers. It is probably the power of context followed by deliberate practice, more than talent, which influences a teacher's level of competency. A good case for this can be made by looking at the ratings of importance in the development of expertise in ice skating by coaches and expert ice-skaters competing at the national team level. Natural ability—talent—was rated 6th of 12 factors in order of importance by the coaches, and 10th by the skaters. Both groups agreed on the 1, 2, and 3 ranks They each rated the desire to be expert number 1, good coaching as number 2, and practice as number 3. Desire, practice and coaching, more than talent are the keys to development of expertise (Starkes, Deakin, Allard, Hodges, & Hayes, 1996). Time commitments for engaging in practice were also studied among skaters, wrestlers, and musicians who desired to reach accomplished levels of performance. There is a dramatic increase in the amount of hours spent practicing each week as they continue to develop as experts. When these athletes and musicians start they practice about 5 h a week. They move to about 10 h a week when they are 4 or so years into their field, and to about 15 h a week 7 years after they begin. They end up putting in 20–25 h a week of practice as they reach their 12th year of their growth as a competitive athlete or accomplished musician. It should be noted that teachers, although loaded with desire, have few opportunities to practice or be coached.

1.2. Defining the expert teacher

The second major issue for this research program is concerned with defining expert teachers. Although inexperience is equated perfectly with novice status in a field, the acquisition of experience does not automatically denote expertise. Thus, it has been hard to have surety that those we identify as expert teachers are actually as highly accomplished as one might want. Our samples of experts often include cooperating teachers (those that train novices), those nominated by peers or administrators, and those that we stipulate on some basis or another as experts. The performance of these experienced "experts" is looked at, often contrasted with novices, and in numerous studies their performance was found to be different in many and profound ways.

But the surety that these were all expert teachers has been lacking. Unlike the small number of fields with tournaments to determine experts, like chess or bridge, one is usually deemed to be an expert by the judgement of others. This is the root of the problem (Sternberg & French, 1992). An expert shaman in some cultures may be an expert by reputational criteria, but regarded as a fake by physicians in Western

countries. Thus in some fields expertise is relative. Furthermore, although "expert" stockbrokers are easy to find, we know that none of them can out perform the stock market with any regularity. So why would we think that shamans or stockbrokers have cognitive processes worth studying or emulating?

Definitional difficulties are quite prominent in the study of expert teachers. One might be considered an expert teacher in one culture, say one like the United States that values student participation in the teaching–learning process. But that same teacher would be considered terrible in another culture, one that purposely limits student participation, like India. Alexander (2001) made this issue quite clear, documenting vast differences in what constitutes acceptable teaching across five cultures. One data set showed that there were teacher interactions with individual students in around 70 percent of the lessons studied in the US, but such interactions with individual students rarely occurred in India. And while students talked directly to each other in about 70 percent of the lessons studied in the US, student to student interactions *never* occurred in the Indian lessons observed. So, vastly different pedagogical tasks are deemed appropriate in these two cultures. A small study of expert and novice teachers in Taiwan makes this point as well (Lin, 1999). Unlike data from the US (e.g., Livingston & Borko, 1989; Leinhardt & Greeno, 1986) differences between expert, beginning, and novice teachers were not found in their thinking about planning or in their curricula decision-making. Given Taiwan's national curriculum, common texts, teacher guides on how to instruct, and a single college entrance examination, this is not surprising. Teacher independence is severely limited in Taiwan, so teachers' cognitions about these areas are equally limited.

We now understand that the cognitive competencies of expert teachers must always be thought of as relative to a culture, perhaps even to a decade in a culture, since what constitutes expert teaching will change in some cultures quite rapidly (Rich, 1993). Context affects teachers and teaching. Note how this differs from the non-relativistic definition of expertise used in Olympic sports like wrestling or ice skating, where the criteria for expertise does not change from culture to culture, and varies only slightly from decade to decade.

The closest we have to a tournament to determine expert teachers is the standardized achievement tests given to students. These are now quite prominent in the United States, and increasing in their use worldwide. But were we to accept high scores on tests as objective criteria for defining teacher expertise, it must then be noted that teachers would be required to demonstrate their expertise through the performance of their students. Thus, teachers' performance would not be evaluated directly, but would instead be a measure of performance once removed. This is quite unlike the methods used to determine experts in chess, bridge or wrestling.

Moreover, there is an empirical problem in requiring high student achievement test results to be a defining characteristic of the expert teacher. Student achievement on standardized tests, and scores on virtually all other outcomes of education, are inherently intertwined with student social class, community social capital, peer effects, and other related factors. Thus the scores that students receive on most measures of educational outcomes are very imperfect indicators of a teachers'

expertise, compared to winning the chess or bridge tournament, achieving Nobel Laureate status, or winning the gold medal in the Olympics.

Despite this, the demand to use student achievement as an indicator of expertise is made by those who rely on the common sense notion that there cannot be teaching without learning. Unfortunately, this common sense notion is not correct. Judgements about the quality of selling, nursing and cooking can be distinguished from whether a customer buys something or not, whether one survives an illness or not, or enjoys the food prepared. There exist standards of competence in these fields so that judgements of quality teaching, selling, nursing and cooking are regularly made independent of their outcomes. Fenstermacher and Richardson (2000) have distinguished between these qualities as the difference between "good" and "successful" teaching. Good teaching is judged through reliance on standards applied to the tasks of teaching and related to norms for professional behavior, including moral considerations. Successful teaching is about whether intended learnings were achieved. Judgements of successful teaching are concerned *not* with the tasks of teaching or professional behavior, but with the achievement of ends.

These arguments are quite important, but may also be thought of as academic in the recent policy context of the United States. Many educators, most of the general public, and particularly the politicians whom the public elects, demand that the performance of expert teachers be judged through their performance in some objective, tournament-like event. These individuals concentrate only on the dimensions of successful teaching and ignore, for the most part, the dimensions of good teaching. Fiscally conservative politicians who might be coerced into paying expert teachers more money, would either like some objective measure to be used to designate expert teachers, or they would like expert teachers to be determined on the basis of their students' performance. These demands are not insurmountable obstacles to the study of expertise in teaching, as will be noted in the following section of this paper. But these are problems that researchers of expertise in bridge, chess or wrestling do not have.

2. Objective definition of expertise and the validity of that designation

A recent program of research and a well-designed validity study answers both demands by the public. Objective criteria for designating expert teachers have been created. This was an exercise in defining the good teacher through specification of what their classroom performance and professional behavior should look like. In addition, the ability of those designated expert teachers to influence student achievement has also been assessed. This was an attempt to identify the successful teacher. The entire research program was designed to find and celebrate good *and* successful teachers (Bond, Smith, Baker, & Hattie, 2000).

The program of research was begun in 1987 by a newly formed National Board of Professional Teacher Standards (NBPTS). In its mission statement the Board promised to establish high and rigorous standards for what accomplished teachers should know and be able to do, and to develop and operate a national voluntary

system to assess and certify teachers who meet those standards. Through standards and assessments the Board intended to identify and certify highly accomplished, expert, or master teachers. The Board has 63 members, over half of whom are classroom teachers. In approximately 30 different areas of teaching, such as middle school language arts, or upper level biology, or elementary school generalist, the Board and its consultants have specified what teachers should know and be able to do (National Board for Professional Teaching Standards, 1994).

Rigorous assessments to become Board certified were prepared for each of the teaching areas. The assessment of the candidates for Board certification includes portfolios and videotapes of classroom teaching that are submitted by each candidate, as well as hours of testing at an assessment center. Preparation for the assessment requires a few hundred hours over a 1-year period. Because the development and scoring of the tests is expensive and time consuming, the charge per candidate for taking the test is over US$2000. The passing rate for these various tests is low, making them a challenge; *a tournament* of sorts, that does identify expert teachers as would a bridge tournament or an Olympic competition. But the question for skeptics remains, do teachers identified as accomplished on the basis of this assessment actually perform in their classrooms in the ways that experts are expected to, and do they affect student achievement in a positive way?

On the basis of the literature (e.g., Berliner, 1994a, b; Shulman, 1987; Shulman & Quinlan, 1995) Bond et al. (2000) chose to specify expert classroom performance as consisting of a number of prototypic characteristics, and invented unique measures to assess each one. For example, following the logic of Sternberg and Horvath (1995) among many others, Bond et al. asserted that the expert teacher (like other experts) has extensive and accessible knowledge. For teachers this would be knowledge about classrooms, subject matter and classroom context. Trained observers and analysts assessed this feature by analyzing and numerically coding teachers' classroom lessons and transcripts obtained from interviews with the teachers. In this case highly trained raters were looking for evidence of organization and re-organization of knowledge, connections of the teachers' knowledge to other school subjects, and the connection of the teachers knowledge to the prior and future learning of their students.

A total of 13 prototypical features of expertise were hypothesized, and measures were created for each feature. For each prototypical feature raters were trained to acceptable levels of reliability and performed their analyses blind with regards to the skill level of the teachers they were assessing. The 13 prototypic features were:

- better use of knowledge;
- extensive pedagogical content knowledge, including deep representations of subject matter knowledge;
- better problem solving strategies;
- better adaptation and modification of goals for diverse learners, better skills for improvisation;
- better decision making;
- more challenging objectives;
- better classroom climate;

- better perception of classroom events, better ability to read the cues from students;
- greater sensitivity to context;
- better monitoring of learning and providing feedback to students;
- more frequent testing of hypotheses;
- greater respect for students; and
- display of more passion for teaching.

The outcomes of instruction for students of expert teachers were hypothesized as well. These included:

- higher motivation to learn and higher feelings of self-efficacy;
- deeper, rather than surface understanding of the subject matter; and
- higher levels of achievement.

To assess these prototypic features of expert teachers two samples of teachers were recruited from among those who had attempted to obtain National Board Certification in the areas of Middle Grade Level/Generalist, or Early Adolescent Level/English Language Arts. One of the comparison groups ($N = 31$) consisted of those who passed the National Board tests, the other comparison group consisted of those who did not achieve Board certification through the assessment tests ($N = 34$). All the teachers were well experienced, had prepared diligently for the examinations, and spent considerable amounts of money to demonstrate they were highly accomplished teachers. This is important because the comparison of the prototypical features of expertise, and of the outcomes of the two groups, were not between expert and non-expert. These comparisons are between equally experienced, well-prepared teachers, all of whom thought they were highly accomplished. Thus this was a very conservative investigation of whether the Board assessments could really identify expertise in teaching.

The results of this recent study are quite remarkable. The Board certified teachers, in comparison to those that failed to meet the Board standards on the assessments, excelled on each and every prototypical feature, with statistical significance of those differences achieved in 11 of the 13 comparisons of the features. When looked at as effect sizes, the differences between these two highly experienced groups ranged from just over one-quarter of a standard deviation to 1.13 standard deviations in favor of the Board certified teachers. Thus, teachers found to be experts on the basis of the assessments of the NBPTS were anywhere from 8 percentile ranks to 37 percentile ranks higher on measures of their use of knowledge, the depth of their representations of knowledge, their expressed passion, their problem-solving skills, and so forth.

When discriminant function analysis was performed, about 85 percent of these highly experienced, well-prepared teachers comprising these two groups could correctly be differentiated from each other. The features with the greatest ability to discriminate between the expert/non-expert teachers were the degree of challenge

that the curriculum offered, the teachers' ability for deep representations of the subject matter, and the teachers' skillfulness in monitoring and providing feedback to his/her students. This study provides validity for the assessment program. But what about student outcomes?

Over a dozen scales were used to measure the motivation and self-efficacy of the students of these two groups of teachers. The results revealed few differences.

Student achievement was evaluated through written assignments. But covariates reflecting initial ability of the students could not be obtained. This untrustworthy data set did reveal, however, that the Board certified teachers had students who performed better on the writing assignment. But the mean scores for the two groups do not differ significantly, and the results are probably not interpretable.

On the analysis of student work samples, however, 74 percent of those obtained from the students of Board certified teachers demonstrated higher understanding through more relational and more abstract student work. Only 29 percent of the work samples from the students of the non-Board certified teachers showed these characteristics. The authors of this study note that the NBPTS, through its assessments, is "identifying and certifying teachers that are producing students who differ in profound and important ways from those taught by less proficient teachers. These students appear to exhibit an understanding of concepts targeted in instruction that is more integrated, more coherent, and at a higher level of abstraction than understanding achieved by other students" (p. 113).

In sum, the Board certified teachers who were designated as experts from rigorous assessments, met the criteria for expertise set forth in the prototypic model. And they had students whose work samples were of higher quality than a comparable group of experienced, well-prepared, and confident teachers. This study identified both good and successful teachers. How much more might these teachers have shined if they were compared to a novice, or less prepared, or less confident group? And would not it have been nice to learn of their life histories and about the role of context, practice and ability in their development?

Neither issues about talent, practice, or context and their affects on expertise, nor the definitional issues that the field must grapple with, provide insurmountable problems for studying expertise among teachers. The prototypical model derived from scores of studies across fields as diverse as taxi driving, physics problem solving, race-track handicapping and teaching have yielded propositions about the nature of expertise in teaching that now seem firmly validated. Two conclusions can be reached. First, the use of data from the study of experts in other fields is now more clearly warranted than in the past. This is because the prototypical features derived from these wide-ranging studies have been validated. Second, we can state with great authority that experts in teaching do, indeed, share characteristics of experts in more prestigious fields such as chess, medical diagnosis, and physics problem solving. This point leads to a declaration: *There is no basis to believe there are differences in the sophistication of the cognitive processes used by teachers and experts in other fields.*

3. Propositions about expert teachers

Propositions derived from research about expertise set the stage for (the now) validated prototypical set of features of expert teachers. Many of these were reviewed in greater detail in Berliner (1994a, b) and these served to help the Board derive its model of expertise. These propositions included evidence derived only from studies of teaching expertise. Persuasive evidence from more than one research program seemed to support the following propositions:

- expert teachers excel mainly in their own domain and in particular contexts;
- expert teachers develop automaticity for the repetitive operations that are needed to accomplish their goals;
- expert teachers are more opportunistic and flexible in their teaching than are novices;
- expert teachers are more sensitive to the task demands and social situations surrounding them when solving problems;
- expert teachers represent problems in qualitatively different ways than do novices;
- expert teachers have faster and more accurate pattern recognition capabilities;
- expert teachers perceive more meaningful patterns in the domain in which they are experienced; and
- expert teachers may begin to solve problems slower, but they bring richer and more personal sources of information to bear on the problems that they are trying to solve.

Comments about some of these propositions are in order, based on research not covered in the 1994 reviews and the continuing research on expertise in teaching.

3.1. On expert teachers excelling mainly in their own domain and in particular contexts

Teachers ordinarily seem not to be "general" experts, with unlimited capacity to transfer knowledge from one situation to another. They appeared to have limited knowledge of, say, fourth grade or urban children or history teaching. One expert teacher, Kerrie, whose development was followed for many years by Bullough (Bullough & Baughman, 1997) switched from one school to another and became much less adept as a teacher. Her sense of failure at the new school was utterly demoralizing. In another study, Zeitz (1994) found that literary experts excelled literary novices in interpreting literary texts. But they did not do so when interpreting scientific texts. The expert's knowledge was limited to a particular domain. Stader, Colyer, and Berliner (1990) found that when watching video-tapes of instruction, expert teachers could not decide whether students whom they did not know were comprehending lesson materials or not. Experts' performance at inferring student comprehension from non-verbal cues was no different than that of novices and advanced beginners. But when the experts studied videotapes of students whom they knew, their accuracy in prediction of student comprehension of the lessons went up. Their knowledge of students was specific, depending on things they knew about the child's personality, typical behavior, and past performance. They did not have this knowledge in a generalizable form. Schemp, Manross, Tan, and Fincher (1998) studied physical education experts in and out of their area of expertise. They found that the "same teacher who may be proficient at teaching fitness activities may be woefully lacking when it comes to teaching racket sports. Even the experts' passion for teaching was curtailed if they had to teach in areas in which they were not expert. So a continuing set of studies informs us that expertise is quite often circumscribed.

But research suggests that we do not push this notion of limited and restricted knowledge too far. Rather, a distinction may usefully be made between "adaptive expertise" and a more restrictive kind. Hatano (1990), for example, described the sushi expert that follows recipes and the one that is more creative, the difference, perhaps, between artisans and virtuosos (Bransford et al., 1999). Patel, Kaufman, and Magder (1996) distinguished between specific and generic knowledge among expert physicians. Bertrand, Cellier, and Giroux (1994) remarked on the *general* indexing skills of professional indexers and the *specific* indexing skills that come form practicing indexing in a specific scientific subject area. My own research team in the 1980s privately talked about our "top experts" and other experts in our studies. We had no name for these unique individuals, but the label "adaptive expert" would fit the behavior we saw. Bereiter and Scardamalia (1993) also make a useful distinction about expertise using concepts from the psychology of intelligence. They distinguish between crystallized and fluid expertise. Crystallized expertise consists of intact procedures that have been thoroughly learned through experience, brought forth and used in relatively familiar tasks. Fluid expertise consists of abilities that come into play when an expert confronts novel or challenging tasks.

Adaptive or fluid experts appear to learn throughout their careers, bringing the expertise they possess to bear on new problems, and finding ways to tie the new situations they encounter to the knowledge base they have. Wineburg (1998) has studied a case of this kind. Two expert historians studied and talked aloud about a set of primary documents that were in the area of expertise of only one of these historians. The historian working with documents out of his area at first responded much like novices did when confronted with the same documents (Wineburg & Fournier, 1994). But as this historian worked through the documents, his questions "began to cluster around a set of constructs and relationships that proved crucial to his understanding. Despite early stumbling, … adaptive expertise was evident by task's end, when an interpretive structure that made sense of these issues came into view"(p. 280). For the historian working out of his field fluid expertise was needed. Because of these fluid abilities, in the end, the two historians looked much more alike than they did in the beginning.

So some research informs us that expert, domain-specific contextualized knowledge can often be a limited kind of knowledge. It can even be costly, resulting in stereotypic behaviors and rigid adherence to inappropriate methods (Sternberg & Frensch, 1992). But rich stores of domain specific knowledge also form the basis for adaptive and fluid expertise, where transfer of the experts' knowledge and skills are demonstrated. Adaptive or fluid expertise may also be related to how talent affects development of expertise (see above). It may be that only small numbers of experts in

a field are adaptive or fluid experts. Schiffrin (1996), for example, made the point that in many fields of endeavor it may be that as much as 99 percent of the variance one sees is explainable by deliberate practice. But practice will not explain the performance of the very few top performers in a field. These may be those with talent, and some of that talent may be, or may be the genesis of, adaptive or fluid expertise.

3.2. On the development by expert teachers of automaticity for the repetitive operations needed to accomplish their goals

Automaticity is the goal of a good deal of deliberate practice, as made crystal clear in the study of a golf expert (Starkes et al., 1996). This expert started systematic practice at age 16, hitting 800 balls a day. At a later age he hit the 800 balls a day, then played 54 holes of golf on Saturday and 72 holes of golf on Sunday. Practice resulted in his hitting about 4000 balls a week, perhaps totaling 4 million balls hit in his lifetime. According to this expert, he was always trying to do some particular thing during his practice. It was not mere practice, but deliberate practice, in which he was involved. In the beginning he worked on simplifying his swing, later on hitting to an imaginary spot on a course or to a particular spot on the driving range. His swing became so consistent and straight that when he plays on a course he plays quite swiftly, just going up to the ball and hitting it precisely where he intends to.

Bereiter and Scardemalia (1993) have reminded us, though, that in many fields automaticity has a function beyond mere efficiency. In complex environments automaticity allows cognitive resources to be reinvested in other and higher level cognitive activity. If you do not have to worry about your fingers on the keyboard, a concert pianist can monitor the conductor, the sound, the audience, the vibrato, the pace, etc. Automaticity itself is not "genius", but it provides the hands and feet for genius to emerge (Bryan & Harter, 1899).

The role of deliberate practice in the development of expertise provides a lesson for teacher educators, because practice of any kind is noticeably restricted in the training and education of teachers. Deliberate practice is usually confined to student teaching, and is engaged in by few teachers in the course of their careers. But even during student teaching novice teachers complained they had no time to polish lessons (Livingston & Borko, 1989). The novices in this study most preferred situations where they could teach the same thing twice. One novice said "Just being able to teach the same thing twice means I can iron it out the first time…I'll remember what worked well and what did not work well. And then, [the second time] I've already gone through the material once before, … I've got a much clearer idea of where the snags are in my presentation and where the snags are in their knowledge" (Borko, Livingston, McCaleb, & Mauro, 1988, pp. 65–83). Lesson study, as in some Asian countries, where colleagues watch and critique a lesson, is not found in American and European schools. So the chance to "polish the stones," that is, to hone lessons to perfection, is missing in Western schools (Lewis & Tsuchida, 1998). Lesson study and other forms of deliberate practice and coached

performance seems to be beneficial activities in teacher development, but are not now used extensively.

3.3. On expert teachers being more opportunistic and flexible in their teaching than novices

This difference has been found among all kinds of experts, though in the study of teaching it is best described by Borko and Livingston (1989). Westerman (1991), however, has closely replicated Borko and Livingston's work. Novices in Westerman's study were once again found to be inflexible, sometimes ignoring interesting points students made, letting teachable moments go. One said "I had my lesson plan and I just wanted to get to every part of it and get it finished." Another said, "I just didn't know enough about the topic to discuss it freely." On the other hand an expert said, "I think it's important to be open-ended with kids. I don't care if the lesson doesn't go exactly the way I planned as long as I know where we're heading." Thus expert teachers were found to be much more interactive with their students than novices, who seemed afraid to stray from their lesson plans. Quantitative data exists on this factor as well. O'Conner and Fish (1998) used the Classroom Systems Observation Scale with expert and novice teachers. The scale allows an observer to evaluate classroom environments. These researchers found a significant difference in favor of expert teachers on the dimension of flexibility, a measure of the teachers' adaptability and responsiveness to students. Schemp et al. (1998) confirmed a previous finding that expert physical education teachers have a kind of "plan independence", when teaching in areas of their pedagogical strength. The experts had the "ability to accommodate a range of learner skills and abilities,…appeared more flexible and opportunistic, and demonstrated a willingness to change activities whenever they deemed it appropriate" (p. 351).

From stimulated recall of lessons taught, novice and expert health teachers displayed similar characteristics (Cleary & Groer, 1994). In this study expert teachers often verbalized how their lesson would change, based on what students were doing and how the lesson was progressing. The experts, compared to the novices, seemed capable of "in-flight" decision making in dynamic environments. Novice teachers, on the other hand, stayed close to their lesson plans. In a study of expert and novice Japanese teachers a reason for this well-established phenomena is revealed (Sato, Akita, & Iwakawa, 1993). Teachers were asked to think aloud after watching a lesson by another teacher, and also write a post-lesson summary. The experts engaged in what the authors called impromptu thinking *during* the lesson, but the novices could not do this. The novices reflected on teaching quite well, however, *after* the lesson was done. Not surprisingly, novices did not have the cognitive resources to understand all that was happening in a classroom while it was happening. They could not think aloud because they were cognitively overloaded, a finding described earlier by Carter, Cushing, Sabers, Stein, and Berliner (1988) from my research program.

Sato et al. (1993) concluded that "Experts can teach based upon contextualized thinking, while novices teach regardless of…content, [or] context… . This is the

reason why experts can respond quickly and intuitively to events and creatively improve their teaching. This is also the reason why novices cannot be flexible in their teaching" (pp. 107–108). A good deal of research supports these conclusions. In a related study by Lin (1999), using think-aloud protocols, evidence was found that novices and advanced beginners spend significantly more cognitive resources than expert teachers do thinking about classroom management. This may be a partial explanation for their relative inflexibility. Novices appear to be afraid of losing managerial control. In clinical interviews and from observed lesson segments Ropo (1987) suggested that this is the case. He found novices to be concentrating on their own behavior and management of the lesson, while experts seemed to pay more attention to the contents of students' answers, just as Sato et al. found.

Two points emerge from this well-established set of findings about the flexibility and inflexibility of experts and novices. First is the need for novice teachers to develop functional management routines as quickly as possible. This is needed so they can, as Bereiter and Scardamalia (1993) suggested, reinvest all of the cognitive resources they expend on this concern. In particular, increasing degrees of automaticity in handling problematic classroom activities, might provide the cognitive space and freedom to figure out why classroom problems occur, or what needs modification in the curriculum. This was what Swanson, O'Conner, and Cooney (1990) found in their comparison of novice and expert think-aloud solutions to classroom discipline problems presented in vignette form. Experts thought about the definition of the discipline problem, attempting to represent and define it clearly. Novices did not see much beyond the surface of the problem, jumping quickly to a solution strategy. On the other hand, rather than jumping quickly to a solution strategy, experts were systematically testing hypotheses about possible solutions. Fear and inadequate cognitive resources prevent novices from thinking in this more expert-like way.

Expert teachers learn a lot from experience and so they are often slower to start solving problems than are novices, a finding reported by Berliner (1994a, b), and later replicated by Korevaar (1998). Korevaar assessed the intentions of experienced teachers in dealing with classroom problems. Experienced teachers had more complex ways of handling these problems than did novices, and thus their reaction time to the problems was significantly longer than was that of the novices.

This brings up the second point about this well-established difference in the ways that novice and expert teachers cognize and deal with classroom problems. It suggests an important role for case studies of classroom management in teacher education. With no experience in these often novel situations, coupled with fear of losing control, case studies of classroom management seems a natural way to produce the flexibility of thought that is needed on encountering these situations. Unlike in preparation for the law or business, case study for novice teachers is not yet a significant part of the teacher education curriculum. Yet it appears that case knowledge is a key part of expert knowledge. Memory of cases, for the internist and radiologist in medicine, the player of chess or bridge, or the classroom teacher, contributes to their expert performance. Problems can be classified and solution strategies proposed on the basis of previous experience. When confronted with a new

problem an expert goes through their case knowledge and searches for what Herb Simon has called an "an old friend", a case like the one now before them. When that "old friend" is found, a good start has been made in solving the problem. While case study is not a substitute for genuine experience, its role in teacher education could be greatly enhanced.

But case study is not just recommended to provide experiences that could reduce the time needed to go from an inflexible novice to a more flexible experienced teacher. Case experience is likely to be the method that most often helps one find the "old friend", the previous case that is like the one confronted in the present. It is case knowledge that is probably the basis for positive transfer by experts in complex environments, meaning that the ability to codify and draw on case knowledge may be the essence of adaptive or fluid expertise. Thus the sooner a novice learns how to think about cases, the sooner fluid expertise might develop, if it is to develop at all.

Perhaps case identification and learning, simple mindfulness about learning to teach, is why expert teachers take longer to learn their trade. In Turner's (1995) study, non-exemplary experienced teachers claimed it took them 2.5 years to learn to teach. Exemplary experienced teachers thought it took them almost twice that long, 4.5 years. Learning to teach is not simply learning how to survive the first week of school. It is primarily about learning to codify knowledge in order to draw on it again. And it is probably about complexifying and not simplifying the world. The exemplary teachers in Turner's study also developed a "far more complex view of their working worlds than…non-exemplary teachers. It was this [more complex view] that assisted exemplary teachers to respond to the many challenges, demands, disappointments, and achievements encountered throughout their careers" (p. 224).

3.4. Other findings about expert and novice teachers

Schemp et al. (1998), and Henry (1995) both reached a similar conclusion, namely that experts have a good deal of independence of the opinions of others. They believe their experience and subject matter knowledge give them the autonomy they need to choose the content and pedagogy in their domain of expertise. They are very confident in their domain of expertise. This confidence probably is the reason that they are more evaluative of other teachers than are novices. This suggestion was made from weak data in my program of research (Berliner, 1994a), But this was found as well by Lin (1999). When viewing slides of classrooms, Lin's expert teachers produced three times as many evaluation statements as were made by novice and beginning teachers.

Another weak finding in earlier reviews of this research was that experts, compared to novices, attend more to atypical than typical events during classroom instruction. This suggestion was given support in the work of Allen (1994). She studied a small group of novice, intermediate and expert teachers who were observed and debriefed after they had taught a lesson. Allen found that experts only recalled specifically the atypical behavior of the class or the "problematics" of the lesson. She noted that typical behavior seemed of little or no importance to the expert. Unusual events are recalled with clarity, other events are recalled at a very general level. In my

research program we also looked to see if expert teachers could predict student performance better. Thus, Mullholland (1991) had expert elementary teachers and their novice student teachers each predict the rank order of students taught by them both on standardized tests of achievement. The experts did well, with the correlation between predicted and actual performance averaging 0.74 in reading and 0.73 in mathematics. Correlations between predicted and observed scores for novices were 0.51 and 0.54 for reading and mathematics. Besides the means of these correlations being different, expert teachers in this sample were most often closer to 1.00 in accuracy of their judgements, and novice teachers were much more likely to provide correlations that were not significantly different than zero. Expert teachers could predict their students' achievement level better than could novices working in the same classroom.

Accuracy in prediction seems to be an important characteristic of experts, as revealed in a review of expertise in dynamic environments, defined as nuclear power plants, medical emergency rooms, air traffic control facilities, and the like (Cellier, Eyrolle, & Mariné, 1997). Classrooms, I contend, are not unlike these other high-pressure environments, and the findings from the two research strands are similar. In these dynamic environments expertise is attributed to the experts skill in (1) making accurate inferences about the processes being monitored, (2) anticipating outcomes, and (3) holding a more global and functional view of the situation. A host of studies on cognitive processing of expert teachers would support these conclusions.

4. The development of expertise

Regardless of talent, as experience is gained and reflected on in learning to teach, play chess, or engage in medical diagnosis, some individuals get better at what they do. The developmental model of Dreyfus and Dreyfus (1986) adapted by Berliner (1994a, b) describes how expertise in teaching develops. This heuristic model specifies behavior characteristic of five different stages of development, as individuals move from *novice, to advanced beginner*, to *competent performer*. Some smaller set of these teachers then moves on to *proficient* and *expert* stages of development. These stages and descriptions still seem appropriate, but more recently Glaser (1996) has described the development of expertise differently and more abstractly, conceiving of emerging expertise as a change in agency over time.

Glaser described a progression in terms of three interactive phases. The first stage he calls *externally supported*, involving environmental structuring for initial acquisition of the skills needed by the novice teacher, musician or athlete. The young performer is influenced by the dedication, interest, and the support of coaches, parents, practitioners in the field, and others who are significant in their lives. Glaser labeled the second stage *transitional*. This stage is characterized by a decrease in the scaffolding used for and by the novice performer, accompanied by a concomitant increase in apprenticeship, so that more guided practice can take place. During this time period self-monitoring and self-regulation techniques are learned, and high standards for performance begin to be set. The third stage is called

self-regulatory. In this stage a developing expert controls much more of their own learning environment. Here the conditions for deliberate practice are arranged. The emerging expert receives the feedback they need, and also chooses the level of challenge for their own development. The three stages focus on changing agency during learning, from supported learning to increasingly self-controlled, self-monitored, and self-reinforced learning.

The time for development of expertise differs in every field, but a reasonable estimate for expertise to develop in teaching, if it ever does, appears to be 5 or more years. Turner's (1995) exemplary teachers stated that it takes 4.5 years to learn their trade—not even to be exemplary. Teacher's anecdotes suggest it takes 3–5 years until things that happen in the classroom no longer are surprising. And Lopez's (1995) data suggests that average student achievement on standardized tests goes up every year for the first 7 years of a teaching career.

The US now has 5000 or so Board certified expert teachers, out of a teaching force of about 3,000,000. These remarkable individuals have defied the environments in which teachers usually work. How many more expert teachers might we identify if we had schools where teacher growth is a priority and fostered, and where deliberate practice could take place? Conditions like these are hard to find in education, but at least research now points the way to the contexts and practice conditions that could promote expertise in teaching, should our citizens wish to create them.

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David C. Berliner is Regents' Professor of Education at Arizona State University. He received his doctorate from Stanford University in 1968, and spent his career studying teachers, teacher education, and educational policy. He is a member of the National Academy of Education, and a past president of both the American Educational Research Association and the American Psychological Association. He is the author of over 150 articles, books and book chapters, among them *Educational Psychology* (with N.L. Gage), *The Manufactured Crisis* (with Bruce Biddle) and he served as co-editor of *The Handbook of Educational Psychology* (with Robert Calfee).

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Chapter 2

Learning about and learning from expert teachers

David C. Berliner

College of Education, Arizona State University, Tempe, AZ 85287, USA

Abstract

Studies of expertise in teaching have been informative, despite problems. One problem is determining the relative roles of talent vs. deliberate practice in the acquisition of expertise. When studying teachers, however, a third factor must be considered, that of context. The working conditions of teachers exert a powerful influence on the development of expertise. A second problem is that of definition because expertise in teaching takes different forms in different cultures, and its characteristics change by decade. A distinction is drawn between the good teacher and the successful teacher, characteristics of expertise that are often confused. A prototypical model of expertise is described and found to identify teachers who were both good and successful. Discussed also is the importance of understanding adaptive or fluid expertise, automaticity and flexibility. Finally, the development of teacher expertise is seen as an increase in agency over time.

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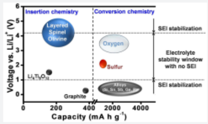
An Outlook on Lithium Ion Battery Technology

Arumugam Manthiram*

Materials Science and Engineering Program & Texas Materials Institute, University of Texas at Austin, Austin, Texas 78712, United States

ABSTRACT: Lithium ion batteries as a power source are dominating in portable electronics, penetrating the electric vehicle market, and on the verge of entering the utility market for grid-energy storage. Depending on the application, trade-offs among the various performance parameters—energy, power, cycle life, cost, safety, and environmental impact—are often needed, which are linked to severe materials chemistry challenges. The current lithium ion battery technology is based on insertion-reaction electrodes and organic liquid electrolytes. With an aim to increase the energy density or optimize the other performance parameters, new electrode materials based on both insertion reaction and dominantly conversion reaction along with solid electrolytes and lithium metal anode are being intensively pursued. This article presents an outlook on lithium ion technology by providing first the current status and then the progress and challenges with the ongoing approaches. In light of the formidable challenges with some of the approaches, the article finally points out practically viable near-term strategies.



■ INTRODUCTION

Lithium ion batteries have aided the revolution in microelectronics and have become the choice of power source for portable electronic devices. Their triumph in the portable electronics market is due to the higher gravimetric and volumetric energy densities offered by them compared to other rechargeable systems. The higher energy density is due to the higher operating voltages of ~4 V resulting from the use of water-free, nonaqueous electrolytes compared to the use of aqueous electrolytes in other systems that limit the operating voltages mostly to <2 V. Lithium ion batteries have also begun to enter the electric vehicle market and are being intensively pursued for grid energy storage as well. Energy, power, charge–discharge rate, cost, cycle life, safety, and environmental impact are some of the parameters that need to be considered in adopting lithium ion batteries for various applications.[1−8] While energy density is the most important factor for portable electronics, cost, cycle life, and safety also become critical parameters along with energy density (driving distance between charges) for electric vehicles. On the other hand, cost, cycle life, and safety become more important than energy density for grid-energy storage. It is desirable to have a fast charge–discharge rate for all three applications.

The performance parameters presented above are largely determined by the properties and characteristics of the component materials used in assembling the batteries as well as the cell engineering and system integration involved. The characteristics of the materials employed rely on the underlying chemistry associated with the materials. Presently, the commercial lithium ion technology is largely limited to cells with gravimetric energy densities of <250 W h kg^{-1} and volumetric energy densities of <650 W h L^{-1}. While the energy densities are not critical for grid storage, volumetric energy densities are often more important for portable electronics and electric vehicles. There is immense interest around the world to push the energy densities to as high as ~500 W h kg^{-1} and >1,000 W h L^{-1}. Accomplishing this goal is challenging; it will need innovations both in the component materials used in the cell and in the engineering involved in fabricating the cells. It should be recognized that the incremental improvements made in energy density since the first announcement in 1991 by Sony Corporation of the commercialization of lithium ion technology is largely due to the progress in engineering as the component electrode materials still remain the same with minor modifications. The sections below provide the current status and where the technology is heading, followed by conclusions.

Energy, power, charge–discharge rate, cost, cycle life, safety, and environmental impact are some of the parameters that need to be considered in adopting lithium ion batteries for various applications.

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■ CURRENT LITHIUM ION TECHNOLOGY

Anodes. The current lithium ion technology is based on insertion-compound cathodes and anodes (Figure 1) and

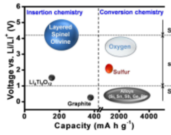

Figure 1. Capacity and voltage ranges of anode and cathode materials for lithium-based batteries. The voltage stability window for the currently used liquid electrolytes in lithium ion batteries and the possibility to widen the stability window by the formation of optimal SEI layers on the electrodes are indicated.

organic liquid electrolytes (e.g., $LiPF_6$ salt dissolved in a mixture of organic solvents, such as ethylene carbonate (EC), dimethyl carbonate (DMC), diethyl carbonate (DEC), ethyl methyl carbonate (EMC), etc.). With an operating voltage close to that of Li/Li$^+$ (~0.1 V vs Li/Li$^+$) and a capacity of 372 A h kg^{-1}, corresponding to the insertion of one Li per six carbon atoms to give LiC_6, graphite (Figure 2) has dominated as an anode in commercial lithium ion cells for the past 25 years. Although the redox energy of graphite lies above the lowest unoccupied molecular orbital (LUMO) of the organic electrolytes used, the formation of a stable solid electrolyte interphase (SEI) layer on the graphite surface in reaction with the electrolyte solvents provides the stability for its operation with a long life (Figure 3). However, the slow lithium diffusion through the SEI could lead to lithium dendrite formation on the graphite surface and internal shorts resulting in catastrophic safety hazards as its operating voltage is close to that of Li/Li$^+$, particularly under conditions of fast charge and at low temperatures. The redox energy of an alternative insertion-reaction anode $Li_4Ti_5O_{12}$ with the spinel structure lies below the LUMO of the electrolyte (Figure 3), i.e., within the electrolyte stability window without the formation of an SEI (Figure 1). With no SEI and with a negligible volume change (<1%), $Li_4Ti_5O_{12}$ offers long cycle life. Unfortunately, with an operating voltage of 1.5 V vs Li/Li$^+$ and a limited capacity of ~160 A h kg^{-1}, it reduces the cell energy density drastically. Nevertheless, it is being employed in cells for grid storage.

Cathodes. For the cathode, there are three choices: layered $LiMO_2$ (M = Mn, Co, and Ni), spinel $LiMn_2O_4$, and olivine $LiFePO_4$ (Figure 2). Each of these three cathodes have their advantages and disadvantages. The layered structure gives the highest practical capacity (currently up to ~180 A h kg^{-1}) among the three, but suffers from structural and/or chemical instabilities during cycling depending on the chemical composition and state of charge (lithium content in the electrode). The structural instability arises from a migration of the transition-metal ions from the octahedral sites of the transition-metal layer to the octahedral sites of the lithium layer via a neighboring tetrahedral site. Mn^{3+} with a low octahedral-site stabilization energy (OSSE, i.e., a small difference between the crystal field stabilization energies in the octahedral and tetrahedral sites), for example, easily migrates and suffers from a structural transition from layered to spinel phase during cycling. Co^{3+} with a high OSSE offers excellent structural stability, but it suffers from poor chemical stability on extracting >50% lithium from $LiCoO_2$ (>50% charge). The chemical instability is due to an overlap of the low-spin $Co^{3+/4+}$:t_{2g} band with the top of the O^{2-}:2p band, resulting in a removal of electron density from the O^{2-}:2p band (i.e., oxidation of O^{2-} ions) for $(1 - x) < 0.5$ in $Li_{1-x}CoO_2$ (Figure 3). In contrast, Mn offers excellent chemical stability as the high-spin $Mn^{3+/4+}$:e_g band lies well above the top of the O^{2-}:2p band. Interestingly, Ni is between Mn and Co in structural and chemical stabilities as Ni^{3+} has higher OSSE than Mn^{3+} and the low-spin $Ni^{3+/4+}$:e_g band barely touches the top of the O^{2-}:2p band. Furthermore, $Co^{3+/4+}$:t_{2g}^{6-x} with a direct Co–Co interaction along the shared octahedral edges and a partially filled t_{2g} band makes $Li_{1-x}CoO_2$ a metallic conductor for $x > 0.1$. In contrast, both $Li_{1-x}NiO_2$ and $Li_{1-x}MnO_2$ remain semiconductors for $0 \le (1 - x) \le 1.0$ as the redox-active or partially filled e_g band is involved in a 90° M–O–M (M = Mn or Ni) bonding. Nevertheless, with a high degree of Ni–O covalence, $Li_{1-x}NiO_2$ offers adequate electronic conductivity. With a 2-dimensional lithium ion diffusion, all three $Li_{1-x}MO_2$ (M = Mn, Co, and Ni) systems offer good lithium ion conduction. Also, Mn is the least expensive and least toxic while Co is the most expensive and most toxic among the three; Ni is in between. Considering the advantages and disadvantages among the three, the industry largely uses compositions, such as $LiNi_{1/3}Mn_{1/3}Co_{1/3}O_2$ (NMC-333), to realize the best possible among the three metal ions.

The $LiMn_2O_4$ spinel cathode with a three-dimensional structure and lithium ion diffusion offers high rate capability and good structural stability without phase transformations. It suffers, however, from a limited practical capacity (<120 A h kg^{-1}) and manganese dissolution caused by a disproportionation of Mn^{3+} ions into Mn^{4+} and Mn^{2+} ions that is initiated by trace amounts of protons generated by a reaction of the lithium

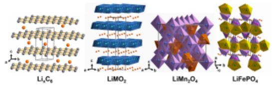

Figure 2. Crystal structures of graphite Li_xC_6, layered $LiMO_2$ (M = Mn, Co, and Ni), spinel $LiMn_2O_4$, and olivine $LiFePO_4$.

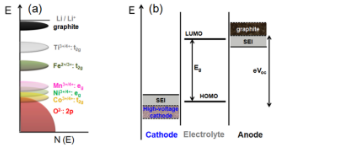

Figure 3. (a) Positions of the various redox couples relative to the top of the oxygen:2p band and (b) schematic energy levels of an anode, cathode, and electrolyte in an open circuit. The possibility to widen the stability window by the formation of optimal SEI layers on the electrodes are indicated in panel b.

salt $LiPF_6$ used in the electrolyte with trace amounts (ppm levels) of water present in the electrolyte. The olivine $LiFePO_4$ cathode, on the other hand, offers good thermal stability and safety without oxygen release as the covalently bonded PO_4 groups tightly hold the oxygen, but suffers from limited practical capacity (<160 A h kg^{-1}), particularly limited volumetric capacity, lower operating voltage of ~3.4 V, and poor electronic and lithium ion conductivity. Although the $Fe^{2+/3+}$ redox couple lies at a much higher energy than the $M^{3+/4+}$ (M = Mn, Co, and Ni) couples, the inductive effect, first recognized by Manthiram and Goodenough in the 1980s with polyanion cathodes, lowers the $Fe^{2+/3+}$ energy and increases the operating voltage to ~3.4 V. The limited electronic and ionic conductivity have to be overcome by reducing the particle size to nanosize and coating with conductive carbon, which further decrease the already low volumetric energy density. The volumetric energy density is influenced by the crystallographic density of the structures. The crystallographic density decreases in the order layered > spinel > olivine. Therefore, among the three insertion-compound cathodes currently in play, the layered oxides are the ones that can provide the highest energy density.

■ WHERE IS LITHIUM ION TECHNOLOGY HEADED?

Increasing the Cell Voltage. There is tremendous interest to increase the energy density of lithium ion batteries by increasing the operating voltage or the charge-storage capacity or both. The only option to increase the cell voltage is raising the operating voltage of the cathode as the present anode (graphite) operating voltage is already close to that of Li/Li$^+$. The three cathode structures (layered, spinel, and olivine) offer compositions with operating voltages higher than the currently used voltages of ~4.3 V vs Li/Li$^+$, but the cathode surface with operating voltages >4.3 V is not stable in contact with the organic solvents EC, DEC, DMC, etc. used in the electrolyte. Examples of potential candidates with higher operating voltages are the spinel $LiMn_{1.5}Ni_{0.5}O_4$ (~4.7 V), olivine $LiCoPO_4$ (~4.8 V), and layered $LiNi_{1-y-z}Mn_yCo_zO_2$ with operating voltages >4.3 V to reversibly extract/insert more lithium. Although the cathode–electrolyte interface is presently not stable above ~4.3 V as the cathode redox energy lies below the HOMO of the electrolyte, it could potentially be circumvented by forming an optimum SEI on the cathode surface and thereby raising it above the HOMO of the electrolyte (Figure 3) analogous to that currently achieved with the graphite anode in commercial cells. While much concerted effort over the years has perfected the graphite anode, efforts toward stabilizing the cathode SEI are scarce. In fact, the electrolyte additives and compositions currently employed in commercial cells are largely tailored to making the graphite anode operable. The challenge is that any efforts made to make the cathode–electrolyte interface operable at higher voltages through electrolyte composition and/or additives should be compatible with the graphite anode; in other words, the approaches should not make the graphite–electrolyte interface unstable or damage the current stability achieved with the graphite–electrolyte interface.

Intuitive search for new electrolytes that are compatible with both the anode and cathode interfaces is needed if we are to increase the operating voltage. Organic solvents with compatible lithium salts that can offer a wider electrochemical stability window and support a higher operating voltage need to be developed. Solid electrolytes that support a wider electrochemical stability window are being intensively pursued, but the huge charge-transfer resistance at the solid–solid interface between the electrolyte and electrode and the mechanical stability and cost-effective, large-scale manufacturability of solid electrolytes pose problems. Some examples of solid electrolytes pursued are based on garnet, LISICON, NASICON, sulfide, and poly(ethylene oxide) (PEO). Development of new liquid or solid electrolytes with desired characteristics will enable the utilization of the high-voltage (>4.3 V) cathodes mentioned above and could also offer better safety.

The challenge is that any efforts made to make the cathode–electrolyte interface operable at higher voltages through electrolyte composition and/or additives should be compatible with the graphite anode.

Increasing the Charge-Storage Capacity. In the absence of a practically viable solution at present to increase the cathode operating voltage, much attention is being paid toward increasing the charge-storage capacities of both the anode

and cathode. In this endeavor, anodes and cathodes that undergo a conversion reaction with lithium rather than an insertion reaction have drawn much attention in recent years. While the capacity of insertion-reaction electrodes is limited by the number of crystallographic sites available for reversible insertion/extraction of lithium, the conversion-reaction electrodes do not have such limitations. They display up to an order of magnitude higher capacities (Figure 1).

Examples of conversion-reaction anodes are Si, Sn, Sb, Ge, P, etc., offering much higher capacities than graphite (Figure 1). They have higher operating voltages than graphite, which would lower the cell voltage, but anodes like Si operate at only a slightly higher voltage than graphite. The major challenges with the conversion-reaction anodes are the huge volume changes (up to ~400% depending on the anode and the lithium content compared to <10% for graphite) occurring during the charge–discharge process, pulverization of the particles, continuous formation of SEI, and the consequent trapping of active lithium from the cathode in the anode SEI. Many approaches have been pursued, such as reducing the particle size to nanosize or deliberately leaving space within the active material architecture, but none of them are successful yet to be practically viable. The above approaches drastically increase SEI formation and decrease the volumetric energy density. The particle milling caused by volume changes results in a continuous formation of new surfaces during the charge–discharge process that further aggravates the formation of SEI. The only progress seen so far is incorporating a few % of Si into graphite to increase the charge storage capacity marginally in practical cells. It is a challenge to employ pure alloy anodes in practical cells that can offer adequate cycle life. An alternative is to use lithium metal as an anode, but reversible plating and stripping of lithium metal over a large number of cycles, SEI formation, and volume changes pose daunting challenges.

Examples of conversion-reaction cathodes are sulfur (or Li_2S) and oxygen (or Li_2O_2 or Li_2O), offering much higher capacities than layered, spinel, and olivine cathodes (Figure 1). However, they are met with numerous challenges. The oxygen-based cathodes suffer from clogging by insoluble products, catalytic decomposition of electrolytes, isolating air from air, and poor cycle life, making their practical viability extremely difficult, if not impossible. The challenges with sulfur-based cathodes are much less compared to those with oxygen, and much progress has been made in increasing the active material content and loading, suppressing dissolved polysulfide migration between the cathode and anode, and reducing the electrolyte amount. However, the necessity of pairing a lithium metal anode with sulfur or oxygen cathode poses formidable challenges, unless Li_2S and Li_2O_2 cathodes could be successfully paired with an anode like graphite or Si or practical lithium-containing anodes that could be paired with sulfur or oxygen could be developed.

Recognizing the daunting challenges associated with the conversion-reaction electrodes, the recent focus has also been on near-term future technologies, i.e., turning around the capacity of insertion-reaction cathodes. In this regard, lithium-rich layered $Li_{1+x}(Ni_{1-y-z}Mn_yCo_z)_{1-x}O_2$ oxides became appealing 15 years ago as they offer higher capacity of 250–300 A h kg^{-1}. Unlike the conventional layered $LiMO_2$ oxides, the lithium-rich layered oxides involve an oxidation first of the transition-metal ions to the 4+ state followed by an oxidation of oxide ions and an evolution of oxygen from the lattice during first charge. The potential participation of oxygen in the reversible redox process of $Li_{1+x}(Ni_{1-y-z}Mn_yCo_z)_{1-x}O_2$ as well as in other lithium-rich materials, such as $Li_2Ru_{1-y}Sn_yO_3$, $Li_{1.2}Ni_{0.13}Mn_{0.54}Co_{0.13}O_2$, and Li_2IrO_3, have created much excitement and debate recently. Unfortunately, despite intensive efforts for more than a decade, the lithium-rich $Li_{1+x}(Ni_{1-y-z}Mn_yCo_z)_{1-x}O_2$ oxides suffer from layered to spinel phase transitions that are accompanied by a continuous voltage decay during cycling, inadequate cycle life, and inferior rate capability due to the presence of a significant amount of more localized Mn^{4+}. Overall, the larger the cathode capacity and the amount of lithium extracted, the greater the tendency for Mn migration from the transition-metal layer to the lithium layer and voltage fade with cycling. Although the potential of other lithium-rich oxides mentioned above and the practical viability of oxygen redox need to be fully assessed, it may prove challenging to realize the long cycle life needed, particularly for electric vehicles and grid storage, with significant amounts of holes in the O^{2-}:2p band, i.e., formation of highly reactive peroxide or superoxide species could cause electrolyte oxidation and degrade cycle life; only time will clarify this predicament.

Focusing on High-Nickel Layered Oxides. With the challenges encountered with lithium-rich $Li_{1+x}(Ni_{1-y-z}Mn_yCo_z)_{1-x}O_2$ cathodes, much attention is currently being directed toward increasing the capacity by increasing the Ni content in layered $LiNi_{1-y-z}Mn_yCo_zO_2$. The high-nickel cathodes are emerging as a near-term future technology. As discussed in the previous section, the characteristics of Ni are between those of Co and Mn in almost all the necessary aspects (chemical stability, structural stability, conductivity, cost, and toxicity). More importantly, Ni^{3+} can be fully oxidized to Ni^{4+} without the loss of oxygen from the lattice, unlike in the case of Co^{3+}. Therefore, $LiNiO_2$ is a better preferred layered oxide cathode. Unfortunately, $LiNiO_2$ encounters a different set of challenges. First, it is very difficult to keep all Ni as Ni^{3+} during the synthesis process at higher temperatures (>700 °C), so the existence of part of Ni as Ni^{2+} results in a volatilization of part of lithium and formation of a lithium-deficient $Li_{1-x}Ni_{1+x}O_2$. This implies a cation disorder between Li and Ni and the presence of Ni in the lithium layer can impede the rate capability. Second, $LiNiO_2$ undergoes a series of phase transitions during the charge–discharge process, particularly at deep charge involving the removal of a significant amount of lithium from the lattice. This, again, can lead to a degradation in rate capability. Third, Ni^{4+} is highly oxidizing and reacts aggressively with the organic electrolytes used in lithium ion cells. The reaction results in the formation of a thick SEI layer, which, again, degrades the rate capability, increases the impedance, and consumes active lithium. Fourth, the chemical instability of the highly oxidized Ni^{4+} results in a transformation of the layered oxide to a rock salt $Li_xNi_{1-x}O$ phase on the surface of $LiNiO_2$. Fifth, the highly oxidized and unstable Ni^{4+} also causes concern with thermal runaway. Because of these challenges, $LiNiO_2$ was largely ignored as a possible cathode for decades. The push to increase the energy density, the potential to obtain higher capacity as Ni^{3+} could be oxidized all the way to Ni^{4+}, and the unsolvable problem of the voltage decay associated with the lithium-rich layered oxides have reinvigorated the interest in high-nickel-content oxides during the past couple of years.

With the renewed interest in $LiNiO_2$, the industry has been slowly moving from $LiNi_{1/3}Mn_{1/3}Co_{1/3}O_2$ to increase the Ni content in $LiNi_{1-y-z}Mn_yCo_zO_2$. For example, compositions such as $LiNi_{0.4}Mn_{0.3}Co_{0.3}O_2$ (NMC-433) and $LiNi_{0.5}Mn_{0.3}Co_{0.2}O_2$ (NMC-532)

$Ni_{0.6}Mn_{0.2}Co_{0.2}O_2$ (NMC-622) have become or are becoming commercial now. The driving force to successively increase the Ni content is the ability to increase the capacity, tap density, and volumetric energy density; with Ni contents of ~0.9, practical capacities as high as ~230 A h kg^{-1} could be realized. However, the long-term stability of NMC-622 for thousands of cycles for applications such as electric vehicles still needs to be established. The problems become increasingly serious as the Ni content increases further beyond NMC-622 to NMC-811 or higher. The high-nickel $LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$ (NCA) is used in commercial cells, but the high Al content decreases the practical capacity to ~180 A h kg^{-1}, and NCA suffers from gas evolution issues during cycling.

The push to increase the energy density, the potential to obtain higher capacity as Ni^{3+} could be oxidized all the way to Ni^{4+}, and the unsolvable problem of the voltage decay associated with the lithium-rich layered oxides have reinvigorated the interest in high-nickel-content oxides during the past couple of years.

During the past couple of years, significant understanding has been made on high-nickel cathodes with advanced analytical techniques, which is extremely valuable if we were to successfully employ nickel-rich layered oxides as we move forward to increase the energy density. An in-depth characterization of $LiNi_{0.7}Mn_{0.15}Co_{0.15}O_2$ (NMC-71515), before and after cycling in 1 M $LiPF_6$ in EC-DEC electrolyte, with a combination of X-ray photoelectron spectroscopy (XPS), time-of-flight secondary ion mass spectroscopy (TOF-SIMS), and high-resolution transmission electron microscopy (HR-TEM) reveals that the SEI layer from the cathode surface to the exterior is successively composed of the rock salt $Li_xNi_{1-x}O$ phase, transition-metal fluorides formed by dissolved metal ions, and organic liquid electrolyte decomposition products. Also, the SEI layer grows continuously with cycling. Figure 4a illustrates a TOF-SIMS chemical mapping of the organic electrolyte decomposition products ($^{7}Li_2^{-}$/LiF and $^{7}LiF_2^{-}$) and transition-metal fluorides (MnF_3^{-}) on a secondary particle of NMC-71515 cathode after cycling. Figure 4b shows a TOF-SIMS comparison of the dissolved transition-metal ions (MnF_3^{-}) on two high-Ni cathodes, $LiNi_{0.61}Mn_{0.27}Co_{0.12}O_2$ (undoped NMC with no Al) and $LiNi_{0.60}Mn_{0.27}Co_{0.12}Al_{0.01}O_2$ (1 mol % Al-doped NMC) before and after 3,000 cycles in a full cell with graphite anode and 1.2 M $LiPF_6$ in EC-EMC with 1 wt % vinylene carbonate (VC) electrolyte. It is remarkable that doping with 1 mol % Al drastically suppressed metal ion dissolution from the cathode as the covalent Al–O bonds keep the oxygen tightly bonded, lower the basicity, and discourage

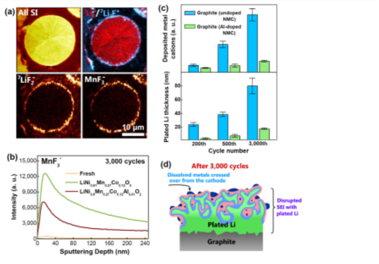

Figure 4. (a) TOF-SIMS chemical mapping of the organic electrolyte decomposition layer and dissolved transition-metal layer in the form of fluorides on an NMC cathode particle. (b) Comparison after 3,000 cycles of the amounts of transition-metal dissolution, forming metal fluorides (e.g., MnF_3^-), from an undoped and a 1 mol % Al-doped NMC cathode relative to that from a fresh electrode. (c) Comparison after 3,000 cycles of the amounts of dissolved transition metals and the calculated thickness of Li metal dendrites on graphite anodes that were paired with an undoped and a 1 mol % Al-doped NMC cathode. (d) Schematic illustrating the evolution of the SEI on graphite anode during cycling under the influence of dissolved transition-metal ion crossover from the cathode to the anode. Reproduced with permission from ref 37. Copyright 2017 American Chemical Society.

transition-metal ion dissolution by acidic attack. Figure 4c compares the amounts of dissolved transition-metal ions and lithium dendrite on the two graphite anodes, one paired with undoped NMC with no Al and the other paired with 1 mol % Al-doped NMC, after 3,000 cycles.[37] It is amazing that the cell with 1 mol % Al-doped cathode has drastically reduced dissolved metal ions and lithium metal plating/dendrite on the graphite anode. Figure 4d schematically shows the buildup of the SEI and plated Li on the graphite anode. The drastic reduction in trapped active lithium in the form of dendrite, enabled by a suppressed metal ion dissolution, leads to superior cycle life over 3,000 cycles for the cell with 1 mol % Al-doped NMC cathode compared to that with the undoped NMC cathode.[37]

Significant performance gains are being realized with stabilized high-nickel layered oxide cathodes through compositional control, including doping and concentration-gradient structures with less Ni on the surface.[37,38] The salt and solvents in the electrolyte also play a dominant role on cathode surface reactivity, SEI formation, metal ion dissolution, cycle life, rate capability, and energy density. Optimal electrolyte compositions that are compatible with and support favorable SEI formation on both the cathode and anode not only could enhance the cycle life under the current operating conditions of <4.3 V but could also enable operation to higher voltages of layered oxide cathodes as well as other cathodes like spinel $LiMn_{1.5}Ni_{0.5}O_4$ and olivine $LiCoPO_4$.

■ CONCLUSIONS

The current lithium ion technology based on insertion-reaction cathodes and anodes will continue for the foreseeable future, despite their limited energy density dictated by the number of crystallographic sites available as well as the structural and chemical instabilities at deep charge. Much effort has been made toward conversion-reaction anodes and cathodes as they offer up to an order of magnitude higher capacities than insertion-reaction electrodes, but their practical viability is met with challenges. Renewed interest in employing lithium metal as an anode and replacing liquid electrolytes with a solid electrolyte has emerged recently as they can offer safer cells with higher operating voltages and charge-storage capacity, but only time will reveal their practical viability. With the challenges encountered with the alternatives (conversion-reaction electrodes, lithium metal, and solid electrolytes), a feasible near-term strategy is to focus on high-nickel layered oxide cathodes, liquid electrolytes compatible with and forming stable SEI on both graphite anode and high-Ni cathodes, innovations in cell engineering to fabricate thicker electrodes and reduce inactive components, and novel system integration to realize safer, long-life, affordable systems.

■ AUTHOR INFORMATION

Corresponding Author

*Phone: (512) 471-1791. Fax: (512) 471-7681. E-mail: rmanth@mail.utexas.edu.

ORCID

Arumugam Manthiram: 0000-0003-0237-9563

Notes

The author declares no competing financial interest.

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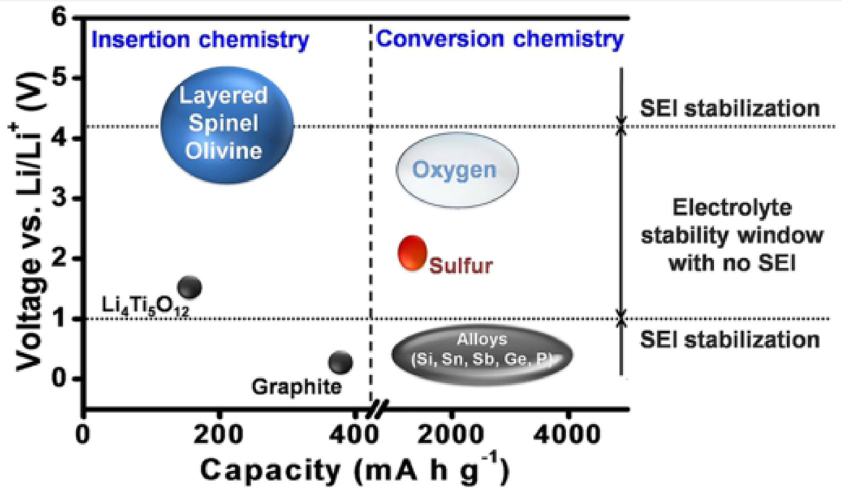
An Outlook on Lithium Ion Battery Technology

Arumugam Manthiram*

Materials Science and Engineering Program & Texas Materials Institute, University of Texas at Austin, Austin, Texas 78712, United States

ABSTRACT: Lithium ion batteries as a power source are dominating in portable electronics, penetrating the electric vehicle market, and on the verge of entering the utility market for grid-energy storage. Depending on the application, trade-offs among the various performance parameters—energy, power, cycle life, cost, safety, and environmental impact—are often needed, which are linked to severe materials chemistry challenges. The current lithium ion battery technology is based on insertion-reaction electrodes and organic liquid electrolytes. With an aim to increase the energy density or optimize the other performance parameters, new electrode materials based on both insertion reaction and dominantly conversion reaction along with solid electrolytes and lithium metal anode are being intensively



pursued. This article presents an outlook on lithium ion technology by providing first the current status and then the progress and challenges with the ongoing approaches. In light of the formidable challenges with some of the approaches, the article finally points out practically viable near-term strategies.

CONCLUSIONS

The current lithium ion technology based on insertion-reaction cathodes and anodes will continue for the foreseeable future, despite their limited energy density dictated by the number of crystallographic sites available as well as the structural and chemical instabilities at deep charge. Much effort has been made toward conversion-reaction anodes and cathodes as they offer up to an order of magnitude higher capacities than insertion-reaction electrodes, but their practical viability is met with challenges. Renewed interest in employing lithium metal as an anode and replacing liquid electrolytes with a solid electrolyte has emerged recently as they can offer safer cells with higher operating voltages and charge-storage capacity, but only time will reveal their practical viability. With the challenges encountered with the alternatives (conversion-reaction electrodes, lithium metal, and solid electrolytes), a feasible near-term strategy is to focus on high-nickel layered oxide cathodes, liquid electrolytes compatible with and forming stable SEI on both graphite anode and high-Ni cathodes, innovations in cell engineering to fabricate thicker electrodes and reduce inactive components, and novel system integration to realize safer, long-life, affordable systems.

Skim reading is your friend

Vs.

CONCLUSIONS

The current lithium ion technology based on insertion-reaction cathodes and anodes will continue for the foreseeable future, despite their limited energy density dictated by the number of crystallographic sites available as well as the structural and chemical instabilities at deep charge. Much effort has been made toward conversion-reaction anodes and cathodes as they offer up to an order of magnitude higher capacities than insertion-reaction electrodes, but their practical viability is met with challenges. Renewed interest in employing lithium metal as an anode and replacing liquid electrolytes with a solid electrolyte has emerged recently as they can offer safer cells with higher operating voltages and charge-storage capacity, but only time will reveal their practical viability. With the challenges encountered with the alternatives (conversion-reaction electrodes, lithium metal, and solid electrolytes), a feasible near-term strategy is to focus on high-nickel layered oxide cathodes, liquid electrolytes compatible with and forming stable SEI on both graphite anode and high-Ni cathodes, innovations in cell engineering to fabricate thicker electrodes and reduce inactive components, and novel system integration to realize safer, long-life, affordable systems.