Using cognitive load theory to help students learn more effectively

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Processing information

Psychologists distinguish between two types of memory

- Limited capacity primary memory ("working memory")
- Unlimited capacity secondary memory ("long term memory")

"Learning" is the process of transfer of new information from working memory to long term memory, typically by associating it with some existing prior knowledge

Hence working memory is of interest when thinking about learning

Information Processing Model

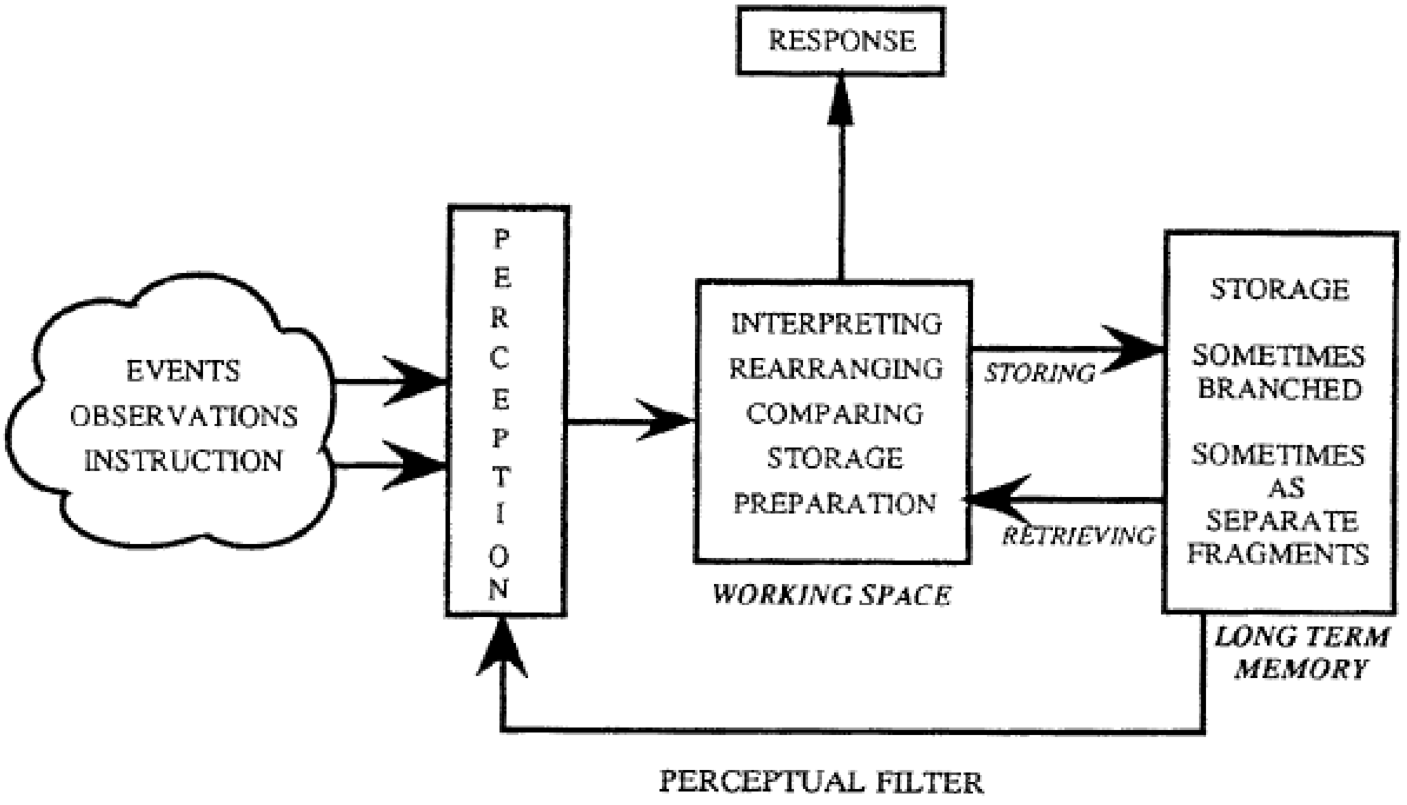
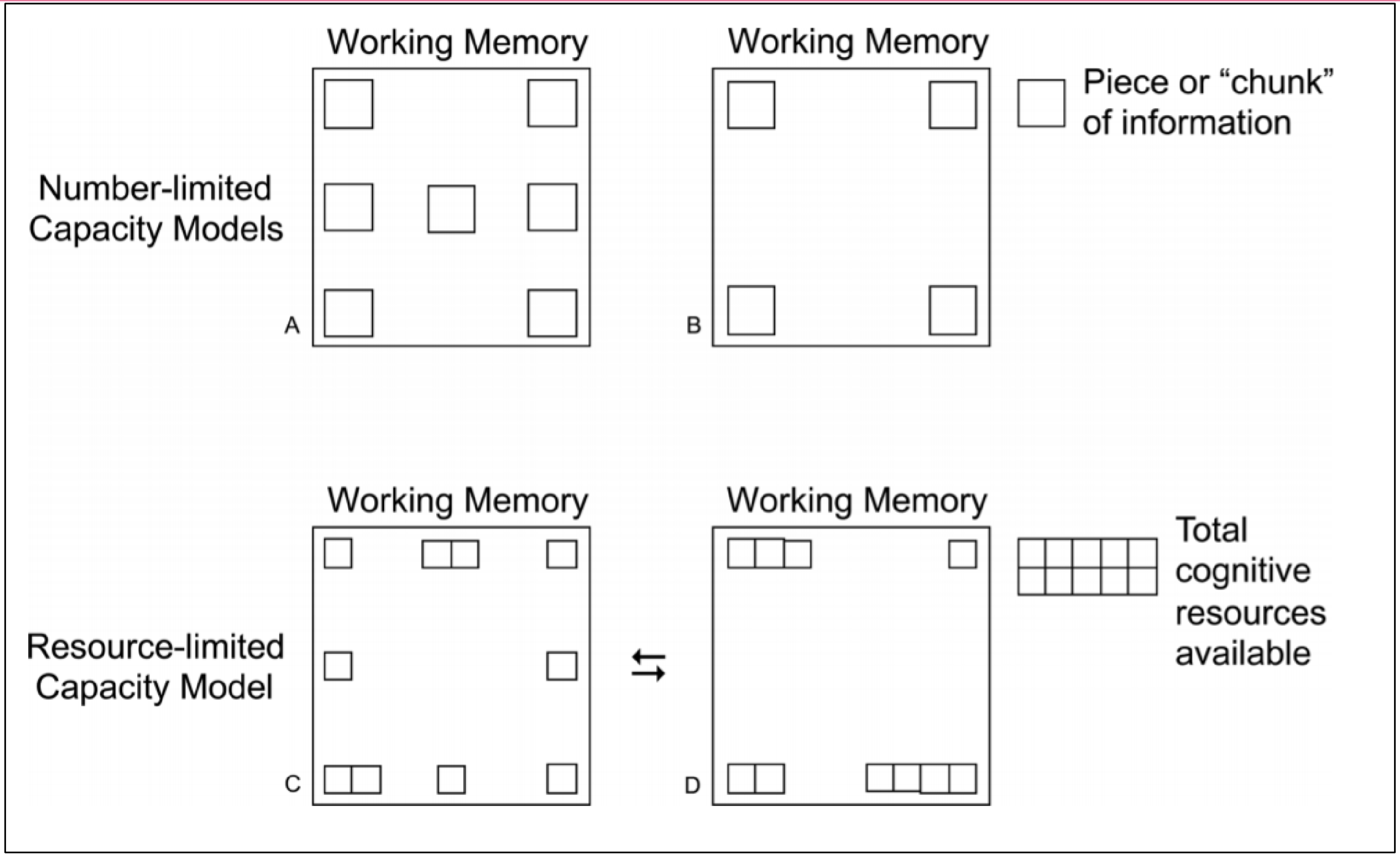


FIG. 1. A model of learning and memory organisation in information processing.

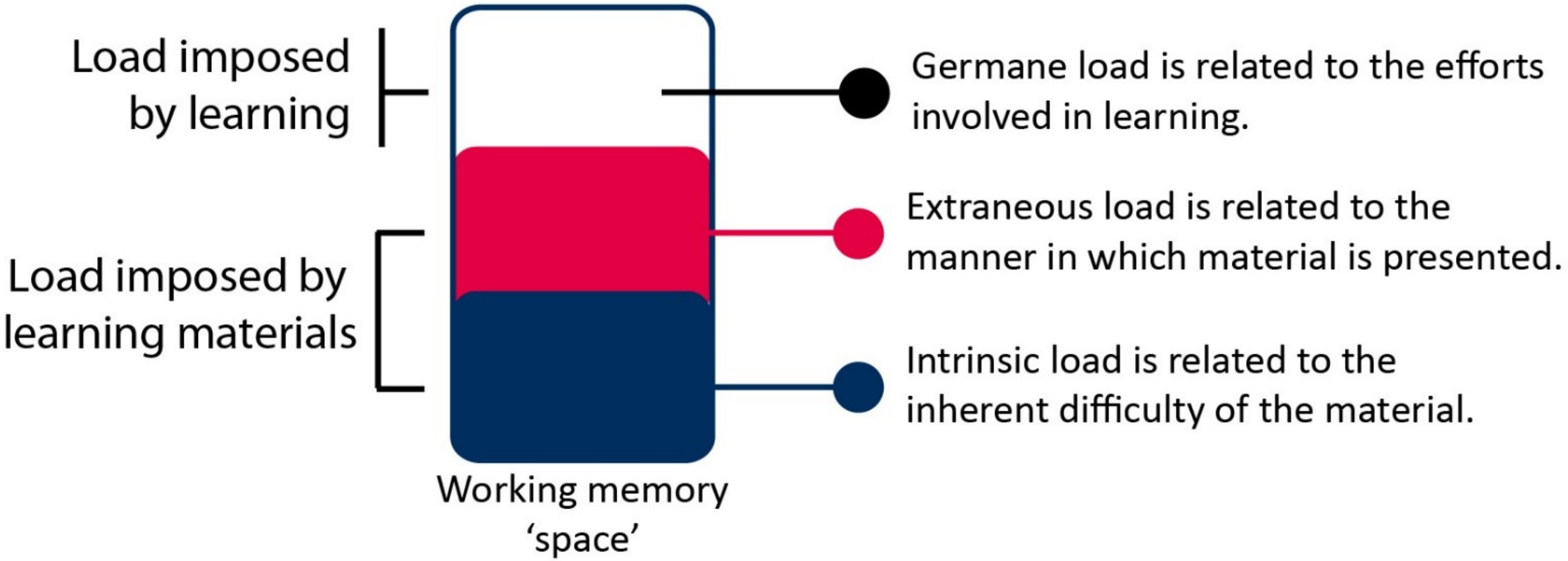
A. H. Johnstone, An information processing model of learning: Its application to an undergraduate laboratory course in chemistry, *Studies in Higher Education*, 1994, **19**, 77-87.

“Limited capacity”



Miller, G. A. The magical number seven, plus or minus two: Some limits on our capacity for processing information. *Psych. Rev*. 1956, **63**, 81–97.
Cowan, N. The magical number 4 in short-term memory: A reconsideration of mental storage capacity. *Behav. Brain Sci*. 2001, **24**, 87–185.
Bays, P. M.; Husain, M. Dynamic shifts of limited working memory resources in human vision. *Science* 2008, **321**, 851–854.

Cognitive Load Theory



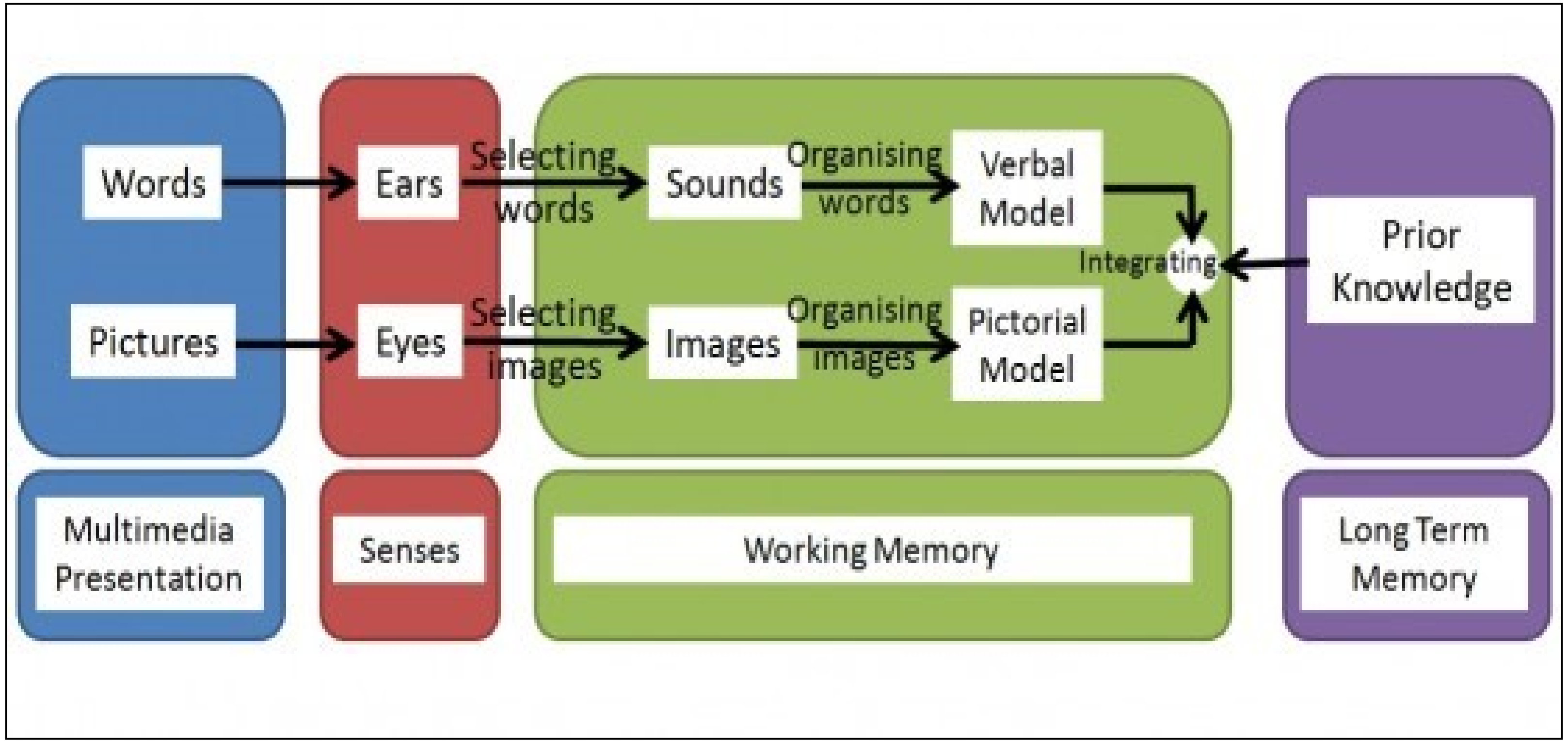
J. Sweller et al., *Cognitive Load Theory*, Explorations in the Learning Sciences, Instructional Systems and Performance Technologies, Springer, New York, 2011.

- Intrinsic Load: Difficulty of route
- Extraneous Load: Quality of Directions
- Germane Load: Actions to get to destination

"Measuring" cognitive load

- Performance
  - *E.g. Stroop Test "Yellow"*
- Subjective
  - *E. g.* Users rate the difficulty of a task
- Physiological
  - *E.g.* Eyes (dilation, blink rate), heart rate, sweat

Cognitive Load and Multimedia

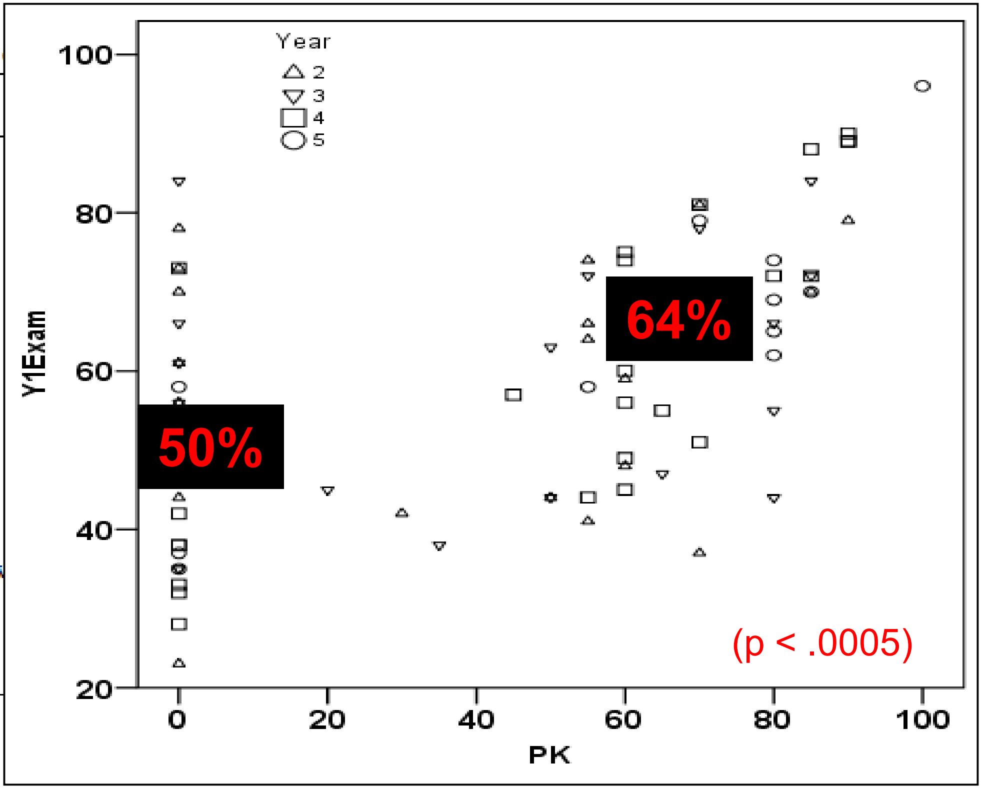


Richard E. Mayer, Multimedia Learning, Cambridge University Press, 2009

Table 3 Correlation matrix showing inter-correlation for all variables in the

	PK	Y1	S1	S2
CAO	0.746**[c]	0.366**	0.205	0.337**
PK		0.569**	0.592**	0.529**
Y1			0.654**	0.684**
S1				0.611**
S2				
Lab				
Dis				
SRA				
SRI				

[a] CAO = CAO points, PK = Prior knowledge, S1 = semester 1 test score, S2
SRI and SRS = student-rated attendance, interest and level of study respectiv
SRI and SRS - which are Spearman's rho.
[b] * = $p < 0.05$, ** = $p < 0.01$
[c] Excluding those without prior knowledge.



No correlation in second and subsequent years

Chemical education research—facts, findings and consequences

A H Johnstone

1981

The 1960s saw the advent of a rash of curricular changes in chemistry in much of the English speaking world. Chem Study and Chem Bond appeared in the US, Nuffield became the trend setter in England and Wales and was exported to several parts of the world. In Scotland, the *Alternative Chemistry Syllabus* appeared in 1962 and was rapidly adopted in all schools. Several curricular packages were tried, with varying success, in Australia and New Zealand and some of their new thinking found its way into Britain.

All of these changes have brought in their wake, feelings of disquiet[1] and there have been attempts to revise them, to supersede them and even to reverse them. Much of this activity is taking place on emotive rather than rational grounds. 'Back to Basics' has become a slogan no more meaningful, but no less potent than 'Power to the People'.

Ten years ago a research team was set up in Glasgow to examine the Scottish Alternative Syllabus and its effects upon schools, pupils, employers and higher education. We were aware that all was not well, and measurement and research were necessary if things were to be put right. It was decided to begin the investigation with first year undergraduates and to ask them for their impression of the course they had just completed at school.[2] Students were invited to choose, from the topics they had met in school, those with which they still had difficulty and would like to be retaught. The results obtained from different universities and over a period of two years showed an unmistakable constancy (*Fig 1*). The frequency with which certain topics were mentioned is shown on the *y*-axis against the topic numbers on the *x*-axis.

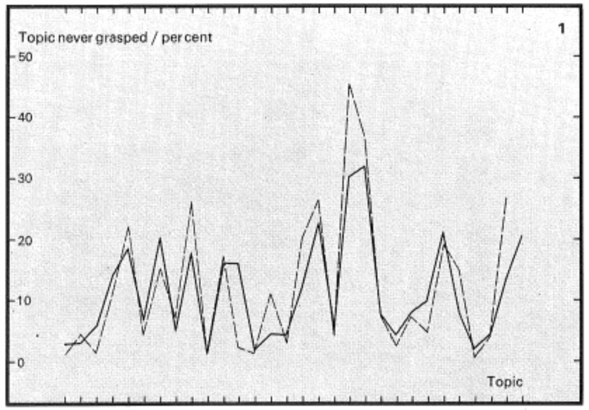
When similar questions were asked of pupils in their final year at school, we obtained peaks in the same places but in general they were more intense, presumably because we were dealing with a less able group than those who had become undergraduates. The main area of discontent were: balancing equations, nett ionic equations, ion-electron half-equations, stoichiometry (especially in solution), conductivity interpretations of neutralisations, E° and cells, Hess's Law, condensation reactions, hydrolysis, saponification, esters and carbonyl compounds.

Various members of the research team were then allocated an area, or group of topics, for further investigation. By a variety of techniques most of these areas were examined for blockages to learning and large amounts of data were accumulated. However, no obvious common factor was apparent and we refused to ally ourselves with any one school of educational thought in our attempts to rationalise the outcomes.

When we came to investigate the organic areas our first hypothesis was that the orientation of a formula was important,[3] *eg* to write an esterification equation, it was customary to present either the acid or the alcohol formula 'backwards' to facilitate the 'lasso operation' for the elimination of water. This hypothesis was shown to be untenable, but it gave us our first clue to the blockages in organic chemistry and eventually to the blockages in several other areas.

It was clear that the problem lay somewhere in the students' perception of organic structural formulae. To probe this, it was decided to use the students' short term memory.[4] When most people are presented with six letters, such as AVPSNQ, and given 10 seconds to memorise them, they can easily recall them in the next 10 seconds. If the sequence is increased to 12 letters, such as AVPSNQZBKLWR, few people can recall them. However, another 12 letter sequence can be easily recalled if it is of the form, BOYCATPINLAW, because English speakers perceive it as four short words. This fits in with the psychological observation that most people can store up to about seven pieces of information in their short term memory. The size of each piece of information depends upon the way it is perceived by the person. This

Fig. 1. Survey results from different universities over two years show the consistent difficulties experienced in some topics.



This is an abbreviated version of the 1980 Nyholm Lecture first presented by A. H. Johnstone on 28 February 1980 at University College, London. The full text of the lecture appears in *Chemical Society Reviews*, 1980, **9**, 365. A. H. Johnstone is head of the chemical education research group at the University of Glasgow, Glasgow, G12 8QQ.

Chemistry in Britain, 1981, **17**, 130-135

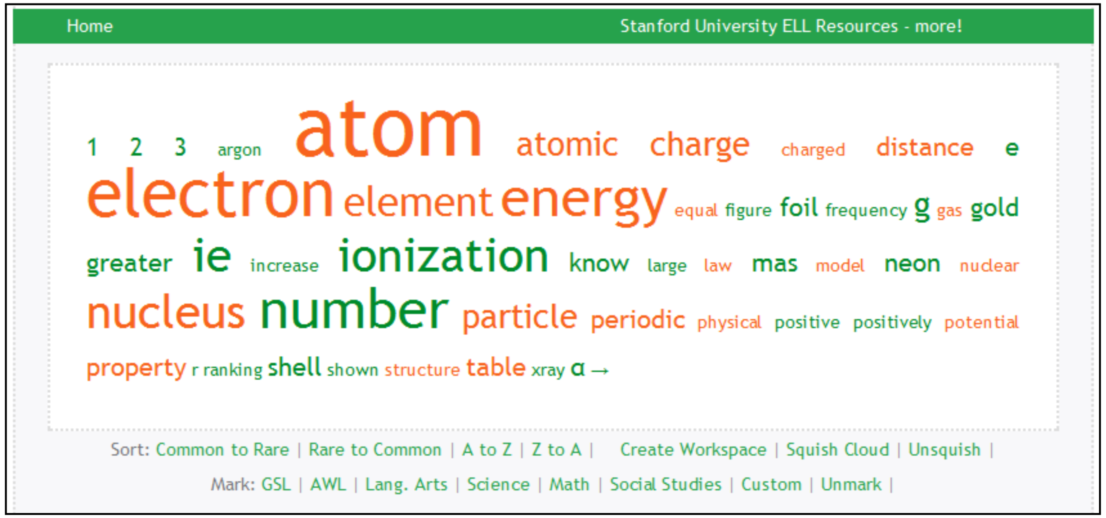
See also *Chemical Society Reviews*, 1980, **9**, 365.

The main areas which seemed to be raising the problems were:

(*a*) Energetics—including Hess's Law,
—E°'s and cells;

(*b*) Stoicheiometry—writing and balancing equations,
ionic equations,
ion–electron half equations,
moles in solution;

(*c*) Organic—particularly esterification, hydrolysis, condensation, saponification, carbonyl compounds.



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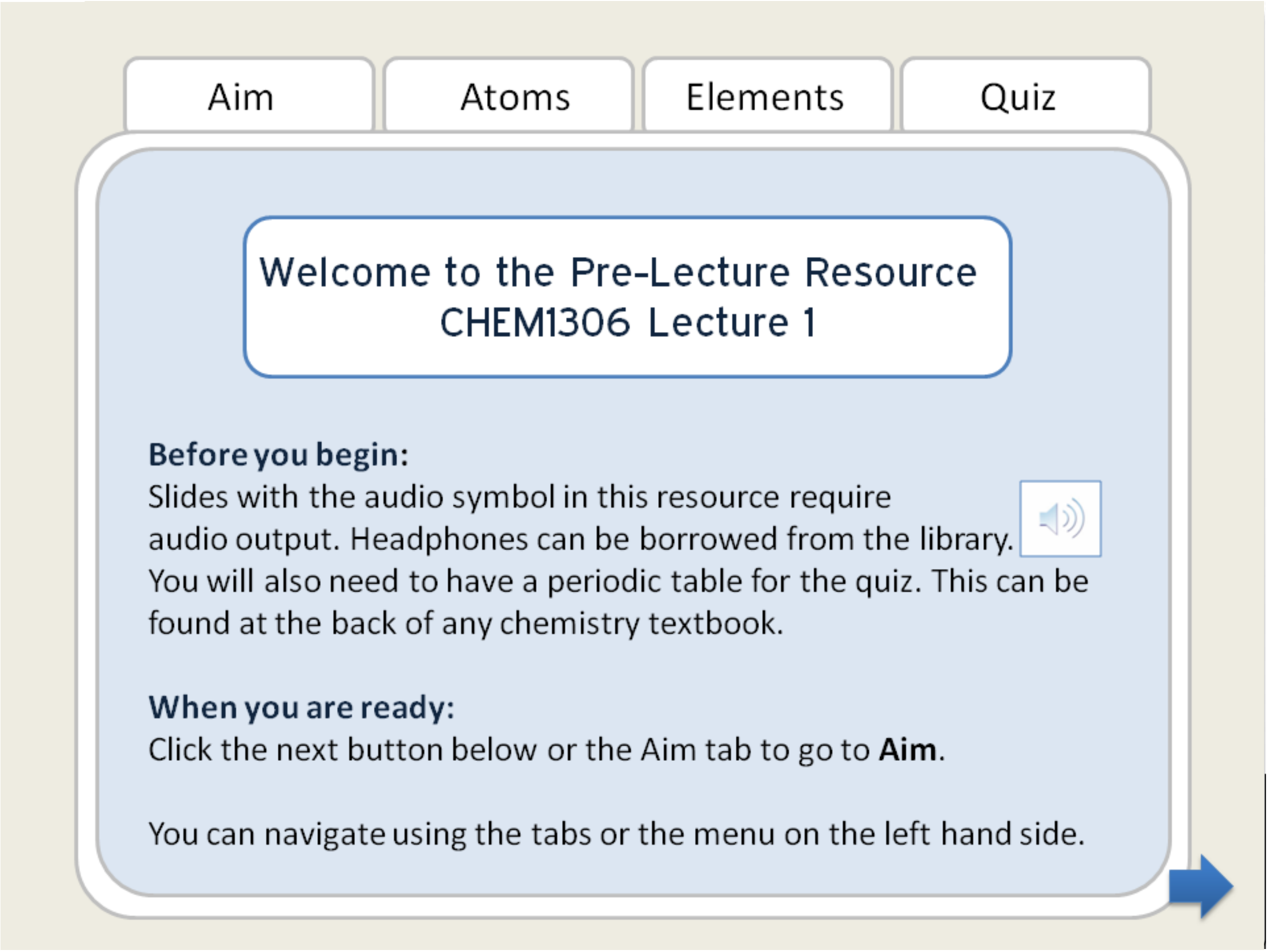
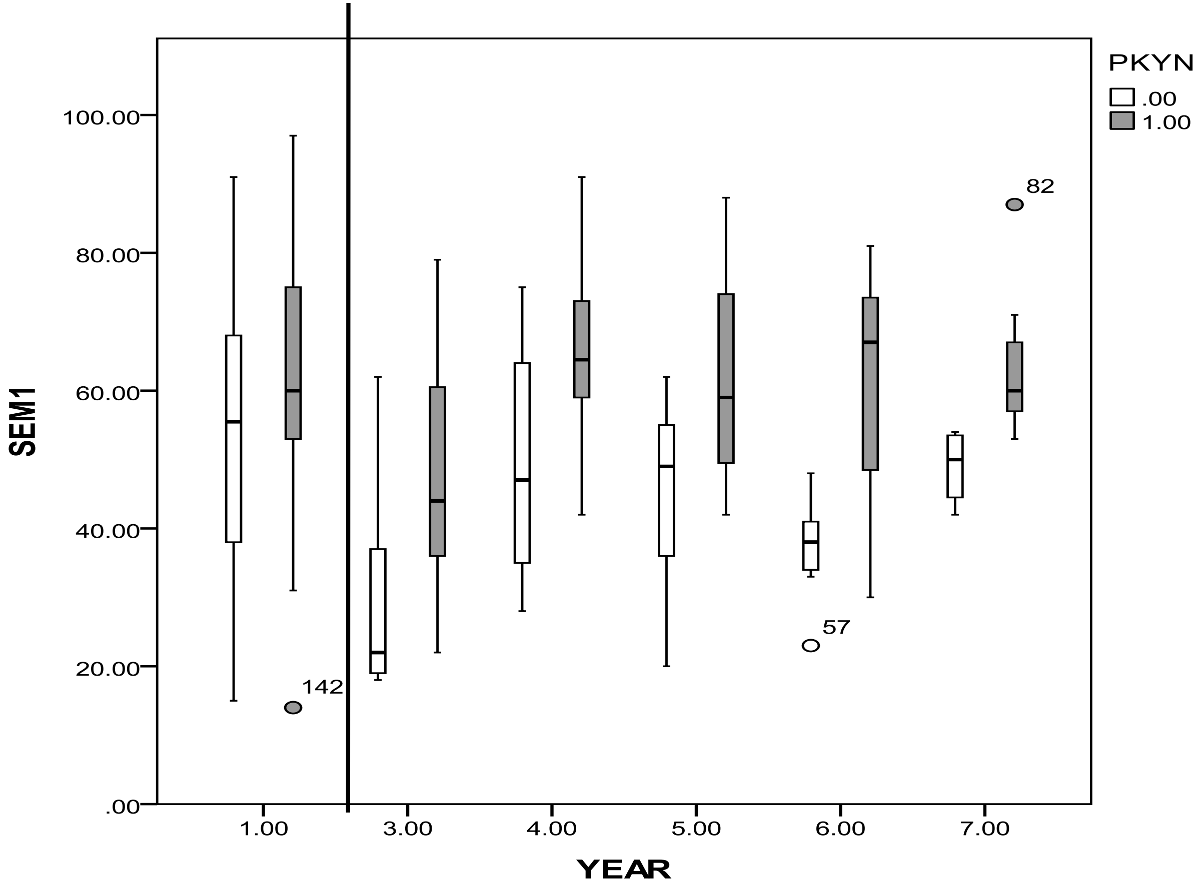
Pre-lecture resources





M. K. Seery and R. Donnelly, The implementation of pre-lecture resources to reduce in-class cognitive load, ***British Journal of Educational Technology***, 2012, 43, 667–677.

Chemistry Education Research and Practice

ROYAL SOCIETY OF CHEMISTRY

REVIEW ARTICLE

Cite this: *Chem. Educ. Res. Pract.*, 2015, **16**, 758

Flipped learning in higher education chemistry: emerging trends and potential directions

Michael K. Seery

Flipped learning has grown in popularity in recent years as a mechanism of incorporating an active learning environment in classrooms and lecture halls. There has been an increasing number of reports for flipped learning in chemistry at higher education institutions. The purpose of this review is to survey

Extraneous load

Corresponding Example from Control Laboratory Manual

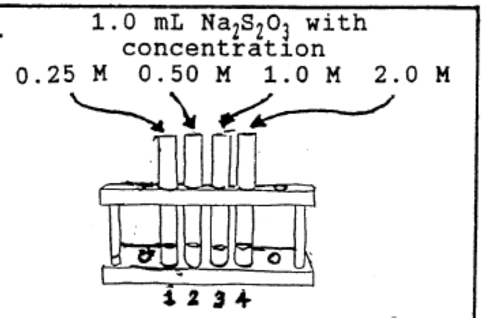
1. Obtain four clean, dry test tubes. Pour 1.0 mL samples of sodium thiosulfate solution ($Na_2S_2O_3$) into the tubes as follows:

   Tube 1 0.25 M $Na_2S_2O_3$
   Tube 2 0.50 M $Na_2S_2O_3$
   Tube 3 1.0 M $Na_2S_2O_3$
   Tube 4 2.0 M $Na_2S_2O_3$

2. Add 1.0 mL 2.0 M hydrochloric acid (HCl) to Tube 1. Record the initial time when mixed together and the final time when the first cloudiness appears in the test tube. Calculate the total reaction time.

Example from Experimental Laboratory Manual

1



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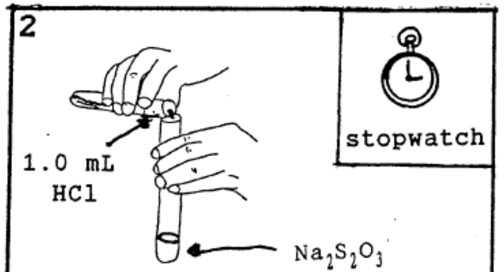

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Dechsri, P., Jones, L. L., & Heikkinen, H. W. (1997). Effect of a labratory manual design incorporating visual information-processing aids on student learning and attitudes. *Journal of Research in Science Teaching*, *34*(9), 891-904.

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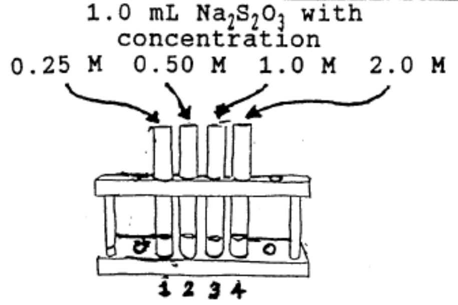

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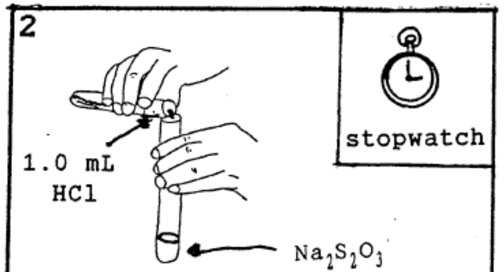

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"*significantly higher scores on measures of achievement and psychomotor skills, and also stimulated students to develop more favorable attitudes toward the laboratory activities*"

Dechsri, P., Jones, L. L., & Heikkinen, H. W. (1997). Effect of a labratory manual design incorporating visual information-processing aids on student learning and attitudes. *Journal of Research in Science Teaching*, *34*(9), 891-904.

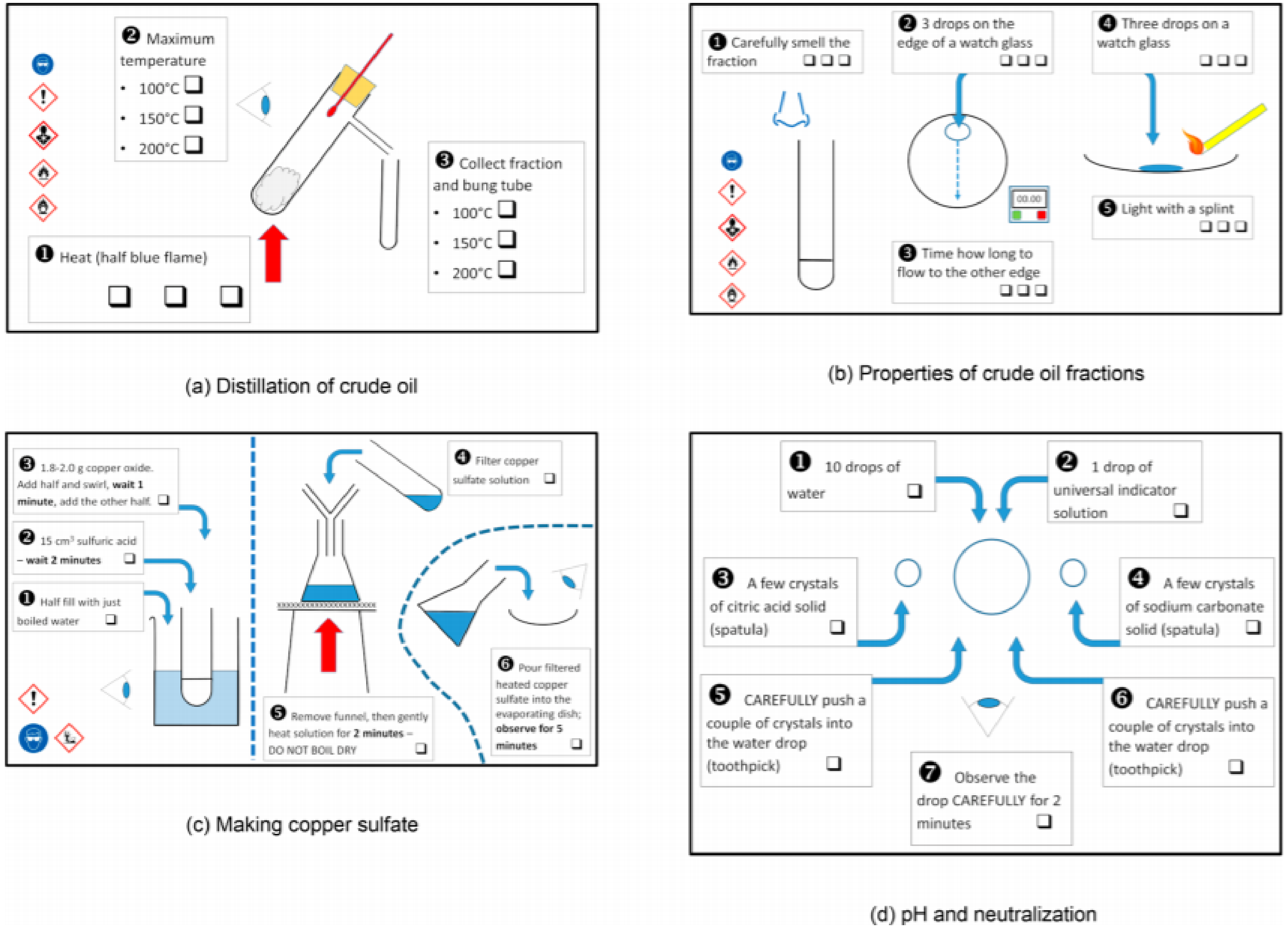

Figure 1. Four integrated instructions for practical tasks. In each, simple apparatus diagrams and textual instructions are combined within one diagram. Each practical step is numbered, and tick-boxes are included to help students to keep track as they work through the practical. Multiple tick-boxes are included when a particular step is repeated multiple times (a,b). An eye pictogram is included where particularly careful observation is required (a,c,d).

"Fewer practical related questions in the (school) lab"

Paterson, D. J. (2019). Design and Evaluation of Integrated Instructions in Secondary-Level Chemistry Practical Work. *Journal of Chemical Education*, *96*(11), 2510-2517.
See also: https://dave2004b.wordpress.com/integrated-instructions/

Mayer's Principles: Using multimedia for e-learning (2017)

Reducing extraneous processing

Coherence Principle
Exclude interesting but irrelevant material as this material reduces cognitive capacity to process essential material in a lesson.

Signalling Principle
Include vocal cues and/or visual highlights to aid the selection and organisation of important information, especially for learners with low prior knowledge.

Redundancy Principle
Graphics with narration alone is more effective than also including on-screen text. Adding one or two keywords as on-screen text has benefit.

Contiguity Principles
Place printed words near any corresponding graphics, and coincide narration with related display.

Managing essential processing

Segmenting Principle
Add self-pacing options to enable learners to process information before continuing.

Pre-training Principle
Provide option to view information on key terms to allow learners to familiarise before having to work with them.

Modality Principle
Present information about a graphic verbally rather than as text so that learners can listen and refer to graphic, especially for system paced dynamic graphics (e.g. videos).

Fostering generative processing

Personalization Principle
Present words in conversational style rather than formal style, including the use of personal pronouns (I and you) in script, especially in early stages.

Voice Principle
Narration should use a human voice rather than a computer voice, and this should match any on screen character.

Embodiment Principle
Drawing graphics as you explain is more beneficial than explaining a presented drawing as it reflects a real-life social interaction.

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From:
Mayer, R. E. (2017) Using multimedia for e-learning. Journal of Computer Assisted Learning, doi: 10.1111/jcal.12197.

Icons: Noun Project (Iconathon, Creaticca Creative Agency, Luis Prado, Edwin Prayogi M, Rodrigo Ramirez, Luke Peek, H Alberto Gongora, Setyo Ari Wibowo, Scott Kennedy)

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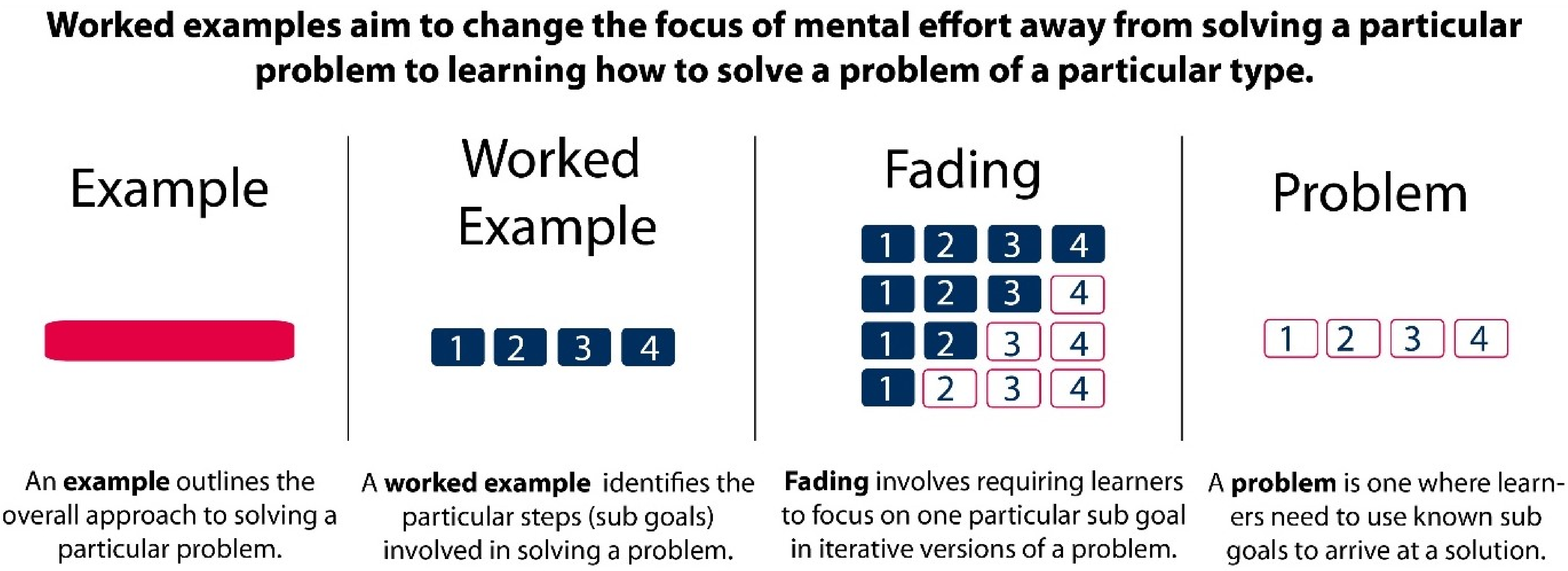
Germane Load



Crippen, K. J., & Brooks, D. W. (2009). Applying cognitive theory to chemistry instruction: the case for worked examples. *Chemistry Education Research and Practice*, *10*(1), 35-41.

Worked examples

Typical quiz

Rank the following in order of increasing (weakest to strongest) conjugate base strength: F^-; I^-; Cl^-

Worked example quiz

Stage 1:	Stage 2:	Stage 3:	Stage 4:
Full answer showing stages for solving problem: 1. Identifying acids 2. Arrange acids in order of strength 3. Identify and rank conjugate base strength	Answer shows stage 1 and stage 2: 1. Identifying acids 2. Arrange acids in order of strength Student completes stage 3 3. Identify and rank conjugate base strength	Answer shows stage 1: 1. Identifying acids Student completes stage 2 and stage 3 2. Arrange acids in order of strength 3. Identify and rank conjugate base strength	Student asked question only: Rank the following in order of increasing (weakest to strongest) conjugate base strength: F^-; I^-; Cl^-

Michael Seery and Christine O'Connor, *E-learning and Blended Learning in Chemistry Education*, in ***Chemistry Education: Best Practices, Innovative Strategies and New Technologies***, Javier Garcia-Martinez, Elena Serrano-Torregrosa, (Eds), Wiley-VCH, 2015

Moving On #1

Thinking more broadly about learning scenarios with a cognitive load perspective

What knowledge do students draw upon for application?

Formative Assessment (Sadler)

Students must develop the capacity to monitor the quality of their own work **during actual production**

Possess a concept of the *standard* being aimed for

Compare the *actual level* of performance with the standard

Engage in appropriate *action* which leads to some closure of the gap

Sadler D. R., (1989), Formative assessment and the design of instructional systems, Instructional Science, 18(2), 119–144.

Changing the feedback model

"Loading up" feedback
Hendry 2013

Hendry G., (2013), Integrating feedback with classroom teaching, in Merry S., Price M., Carless D. and Taras M. (ed.), Reconceptualising Feedback in Higher Education: Developing Dialogue with Students, Routledge, pp. 133–134.

Here is my best effort | Grade work against (assumed) standard | This is the standard

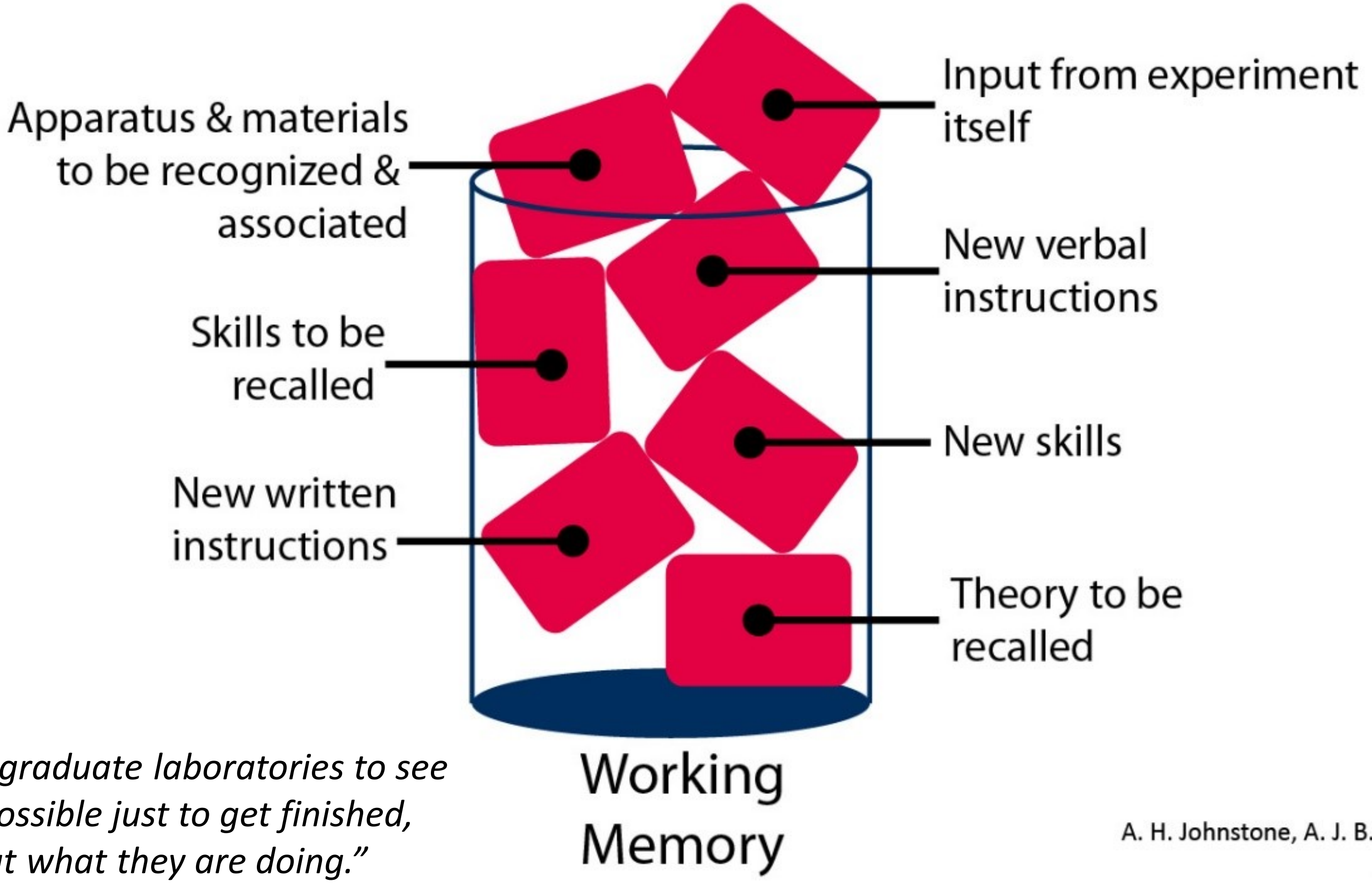
This is the standard (exemplar) | Guidance | Here is my best effort | Grade work against (stated) standard

Students watch EXEMPLAR materials such as video in advance of their lab class.

ASSESSMENT begins in the lab. Students video each other as they demonstrate the technique. Then they peer review.

Students SUBMIT their video for review by instructor to confirm competency is demonstrated.

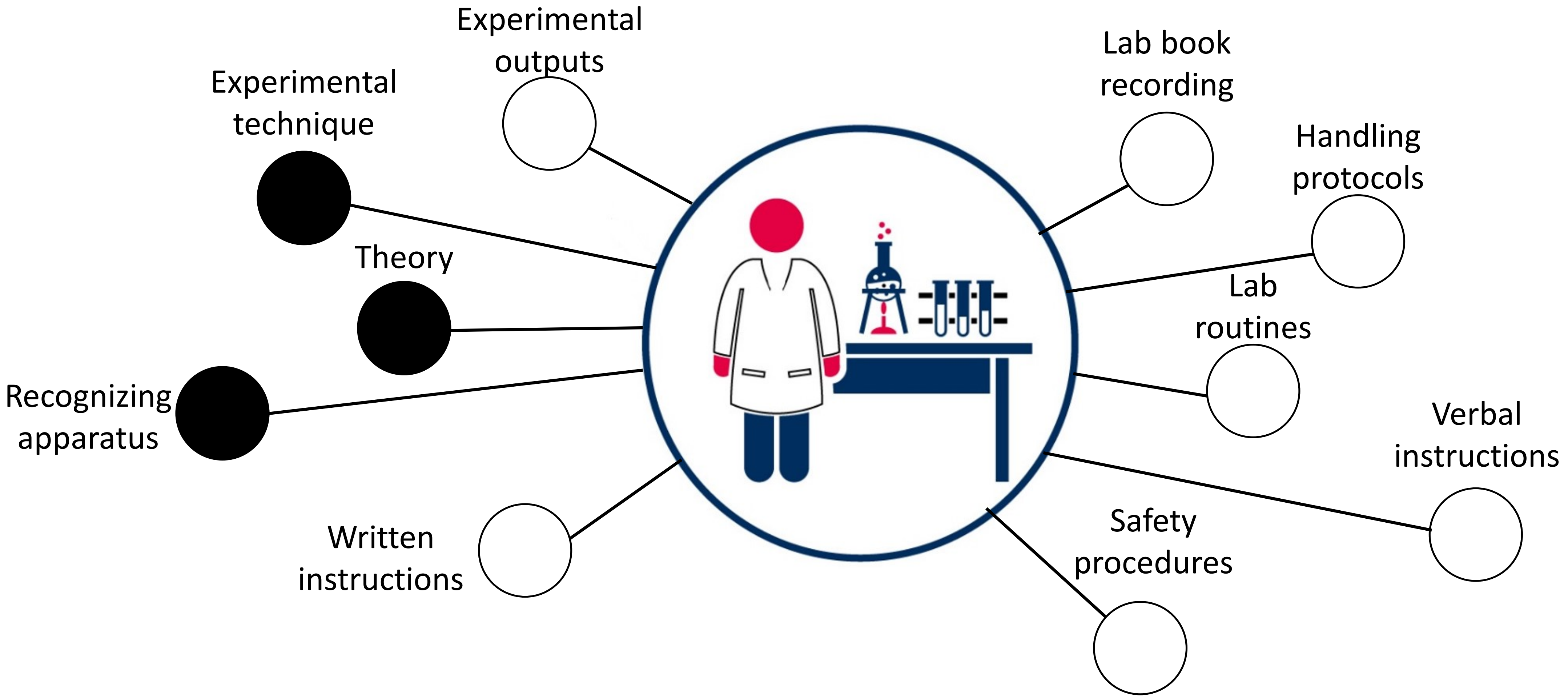
Cognitive Load in Laboratories



"It is not uncommon in undergraduate laboratories to see students working as fast as possible just to get finished, with little or no thought about what they are doing."

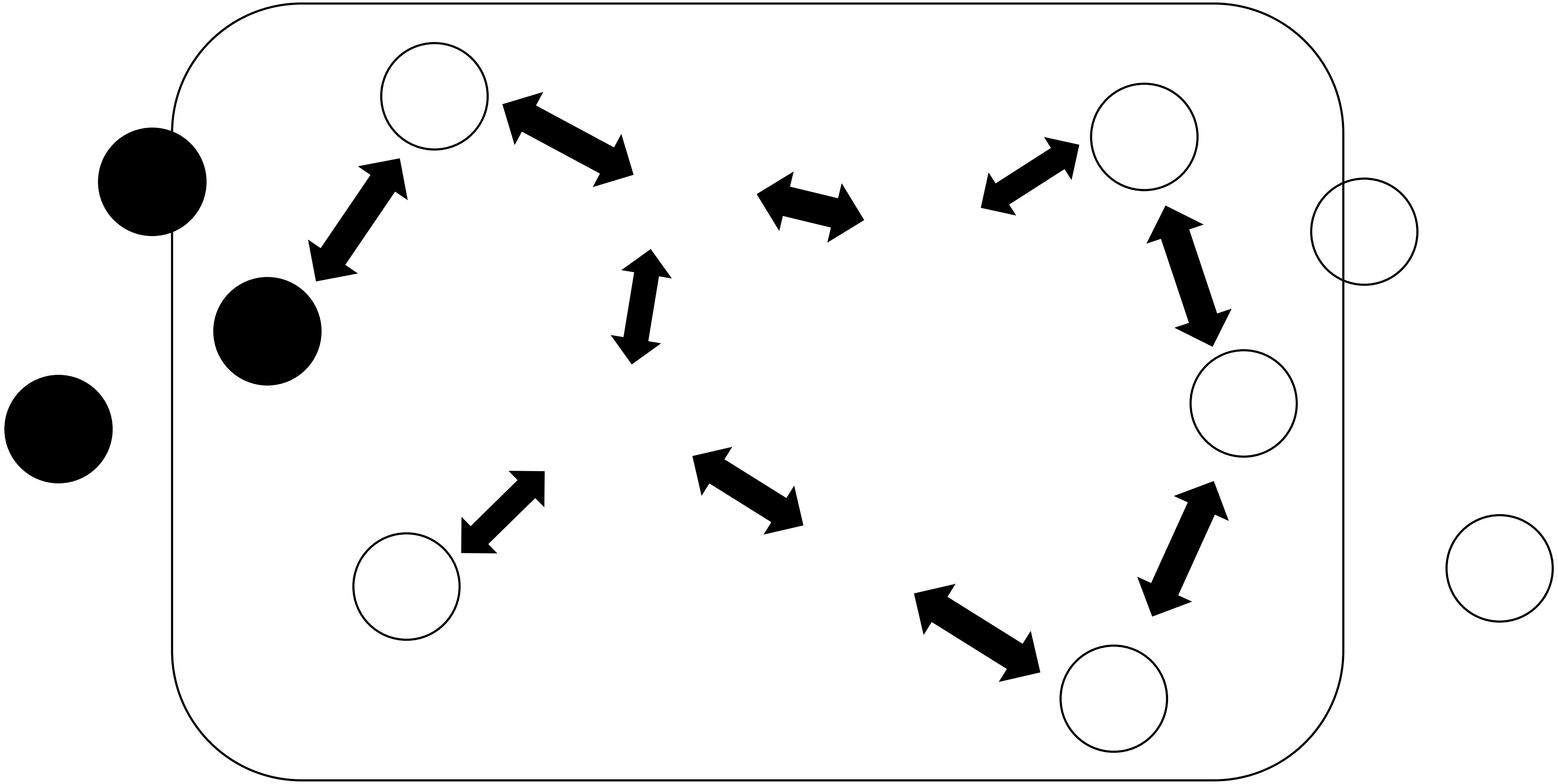
Adapted from:
A. H. Johnstone, A. J. B. Wham, The demands of practical work, *Education in Chemistry*, 1982, **19**, 71-73

Beyond a simple cognitive load framework



Agustian, H. Y. & Seery, M. K. 2017. Reasserting the role of pre-laboratory activities in chemistry education: a proposed framework for their design. *Chem. Educ. Res. Pract.*, **18,** 518-532.

Beyond a simple cognitive load framework



Complex Learning Framework*

Complex learning

(i) aims at the integration of knowledge, skills, and attitudes.
(ii) involves the coördination of qualitatively different constituent skills.
(iii) requires the transfer of what is learned to real settings.

Supporting Learning in a Complex Environment

A focus on whole-tasks rather than part-tasks

Simple to complex sequencing

Information needed to work in a Complex Environment

Supportive information

Procedural Information

VAN MERRIËNBOER, J. J., KIRSCHNER, P. A. & KESTER, L. 2003. *Educational psychologist*, 38, 5-13.

A Survey of Pre-Laboratory Literature

● Experimental
○ Theoretical

● Kempa, *BJET*, 1974 — *Video-taped demonstrations*

○ Krakower, *JCE*, 1977 — *Lap-dissolved slides*

● Moore, *JCE*, 1980 — *Simulations*

○ Kolodny, *JCE*, 1983 — *Quizzes*

○ Isom *JRST*, 1986 — *Pre-lab discussion*

○ Chittleborough, *JCE*, 2007 — *Quizzes with personalised feedback*

● Limniou, *CERP*, 2007 — *Simulations for experimental design*

○ Winberg, *JRST*, 2007 — *Simulations prompting cognitive focus*

● Gallardo-Williams, *JCE*, 2017 — *Student generated videos*

○ Cole, *CERP*, 2017 — *Videos for advanced labs*

H. Y. Agustian and M. K. Seery, Reasserting the role of pre-laboratory activities in chemistry education: a proposed framework for their design, *Chemistry Education Research and Practice*, 2017, **18**, 518-532, DOI: 10.1039/C7RP00140A

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Moving on #2

Students are human beings

Literature review: synopsis of benefits

Category	Summary finding: Pre-laboratory activity tends
Overall	• to have a positive impact on learning in the laboratory.
Experimental	• to increase the work requirements of students outside of formal class time • to increase the efficiency of students' lab work • to result in students reserving questions for more complex techniques • to lead to fewer experimental errors • to result in improved understanding and efficiency of laboratory tasks, especially when students are prompted to consider overall approaches rather than stepwise instructions
Conceptual	• to result in students discussing conceptual aspects more or feeling better informed about conceptual aspects. • to result in students performing better in the laboratory. • to lead students to feeling more autonomous about completing their laboratory work.
Affective	• to enable students to feel more confident about laboratory work, and/or reduced student anxiety about knowing what to do during their practical session. • to motivate students about doing practical work, although there may need to be an extrinsic driver (such as assessment reward) to complete these activities.

H. Y. Agustian and M. K. Seery, Reasserting the role of pre-laboratory activities in chemistry education: a proposed framework for their design, *Chemistry Education Research and Practice*, 2017, **18**, 518-532, DOI: 10.1039/C7RP00140A

Discussion suggestions

- Are there problems just thinking about “bits of information”?
- Is it too utilitarian? Isn’t learning richer than this?!
- Application beyond chemistry/sciences?
- Limitations of CLT (not a theory(!), not summative)?