A Scientific Approach to the Teaching of Chemistry

Norman Reid

Centre for Science Education, University of Glasgow, Scotland

A Scientific Approach to the Teaching of Chemistry

What do we know about how students learn chemistry and how can we make our teaching match this to maximise performance?

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Where are we Going ?

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- Why Chemistry is Difficult
- Information Processing - the Key ?
- How Students Learn
- Bringing in Together
- The Attitude Problem
- A Total Picture

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What does research tell us about learning?
How can we apply it in practice?

Some History

School Curriculum Revolution in Chemistry started in the 1960s

By the mid-1960s, reports emerged in Scotland:

some of the chemistry is too difficult; parallels in other countries

Research Studies:

Where are the difficulties ?

Is there anything we can do?

What are the misconceptions ?

Are there underlying reasons for the problems?

Numerous Curriculum Revisions, especially the USA

What was the actual evidence?

Could we be scientific about teaching and learning ?

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Many Assertions

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Chemistry is abstract
Chemistry is full of concepts
Students hold many misconceptions

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They cannot do mathematics!

More roadshows, more glossy booklets, more advertising, more school visits, more science centres ..... !!

Difficulties Survey (1970)

Most difficult topics

(from upper school as seen by first year students)

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- Redox (eg E°) and ion electron ideas
- Organic topics like esters, proteins, amines and carbonyls, aromaticity

Some Growing Ideas

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Success might be linked to Information Load

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Questions could be analysed by information load

Exploring Information Load

Exploring Information Load

I shall give you some dates

Exploring Information Load

I shall give you some dates

Turn the dates into numbers

Exploring Information Load

I shall give you some dates

Turn the dates into numbers

Put the numbers in ascending order

Trial Run

Trial Run

8 March 96

Trial Run

8 March 96

8 3 9 6

Trial Run

8 March 96

8 3 9 6

3 6 8 9

26 December

1 2 2 6

June 1984

1 4 6 8 9

8 May 1996

1 5 6 8 9 9

11 January 1901

0 1 1 1 1 1 9

23 December 1873

1 1 2 2 3 3 7 8

5.30 am 16 November 2007

0 0 0 1 1 1 2 3 5 6 7

5.30 am 16 November 2007

0 0 0 1 1 1 2 3 5 6 7

0 0 0 1 1 1 2 3 5 6 7

Working Memory

Working Memory

- Limited capacity: 7 ± 2
- Fixed genetically
- Grows with age
- Can be used efficiently or otherwise

Measuring Working Memory Capacity

Measuring Working Memory Capacity

Digit Span Backwards Test

Measuring Working Memory Capacity

Digit Span Backwards Test

Recall numbers backwards

Measuring Working Memory Capacity

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Recall numbers backwards

Figural Intersection Test

Measuring Working Memory Capacity

Digit Span Backwards Test

Recall numbers backwards

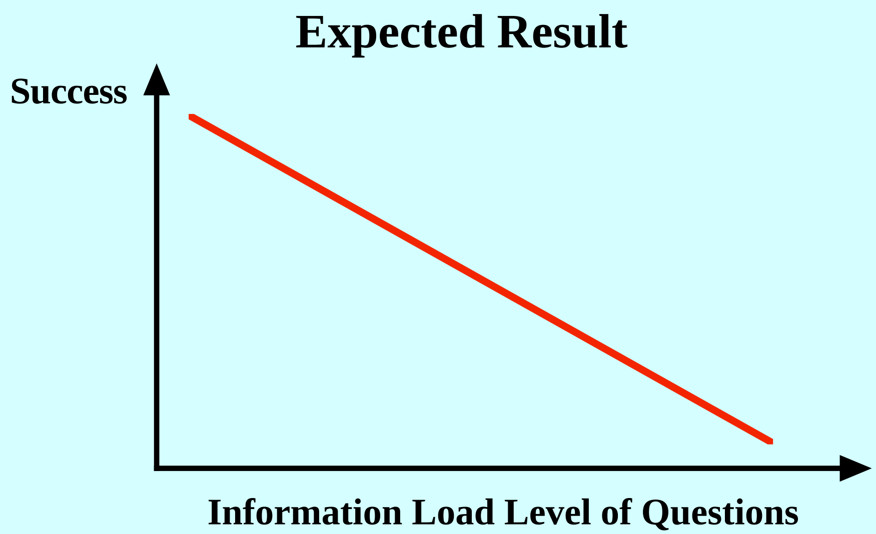
Figural Intersection Test

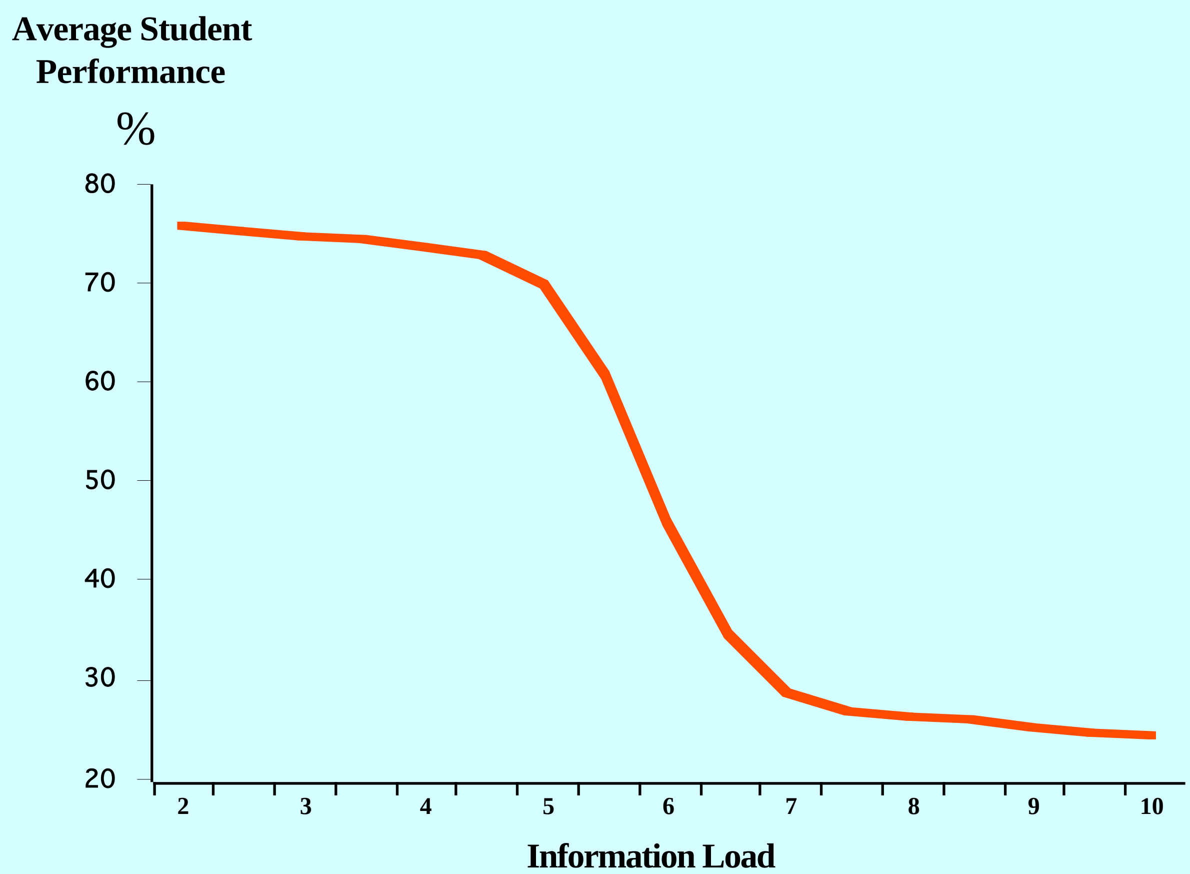
Finding overlap between several geometrical shapes

Information Load and Success

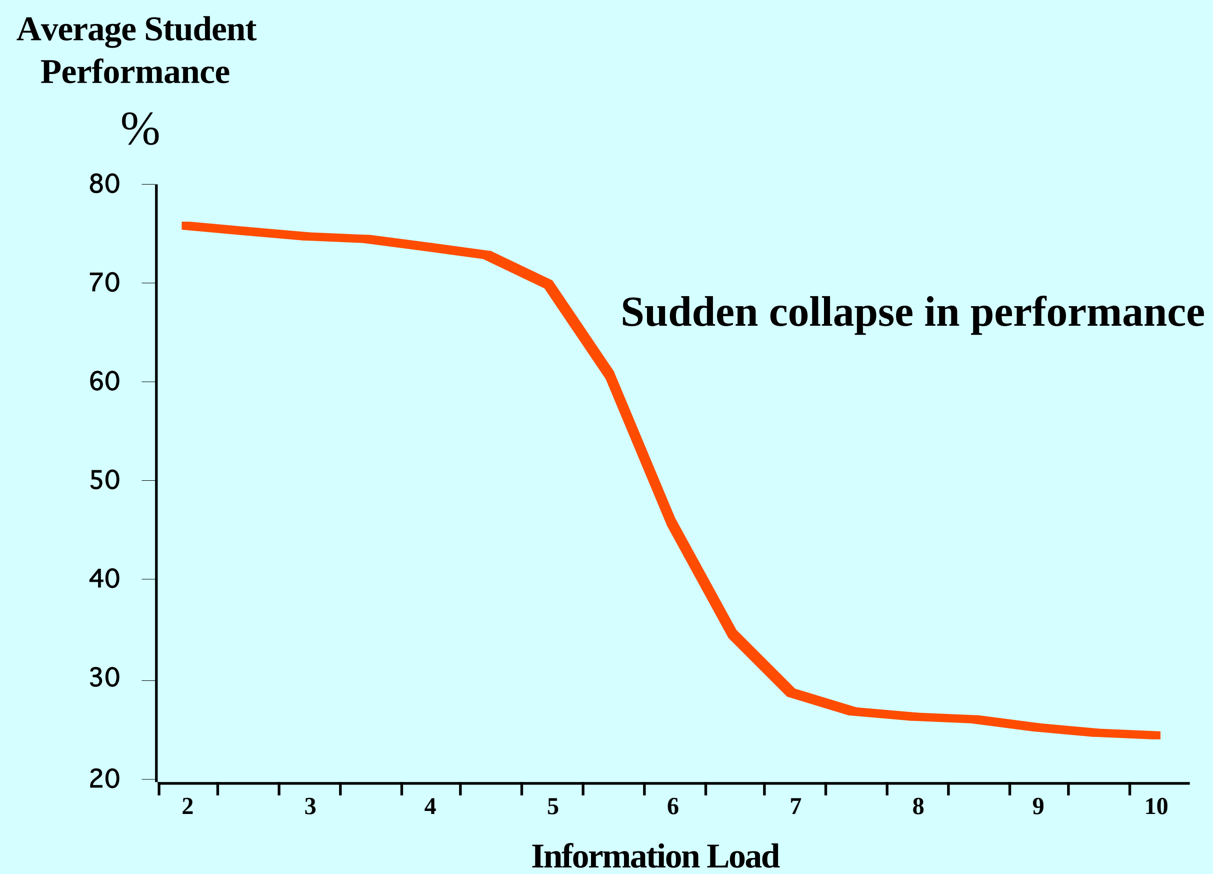
Reasonable hypothesis:

As load increases, success will fall.





Average Student Performance
%
80
70
60
50
40
30
20
2
3
4
5
6
7
8
9
10
Information Load


Average Student Performance
%
80
70
60
50
40
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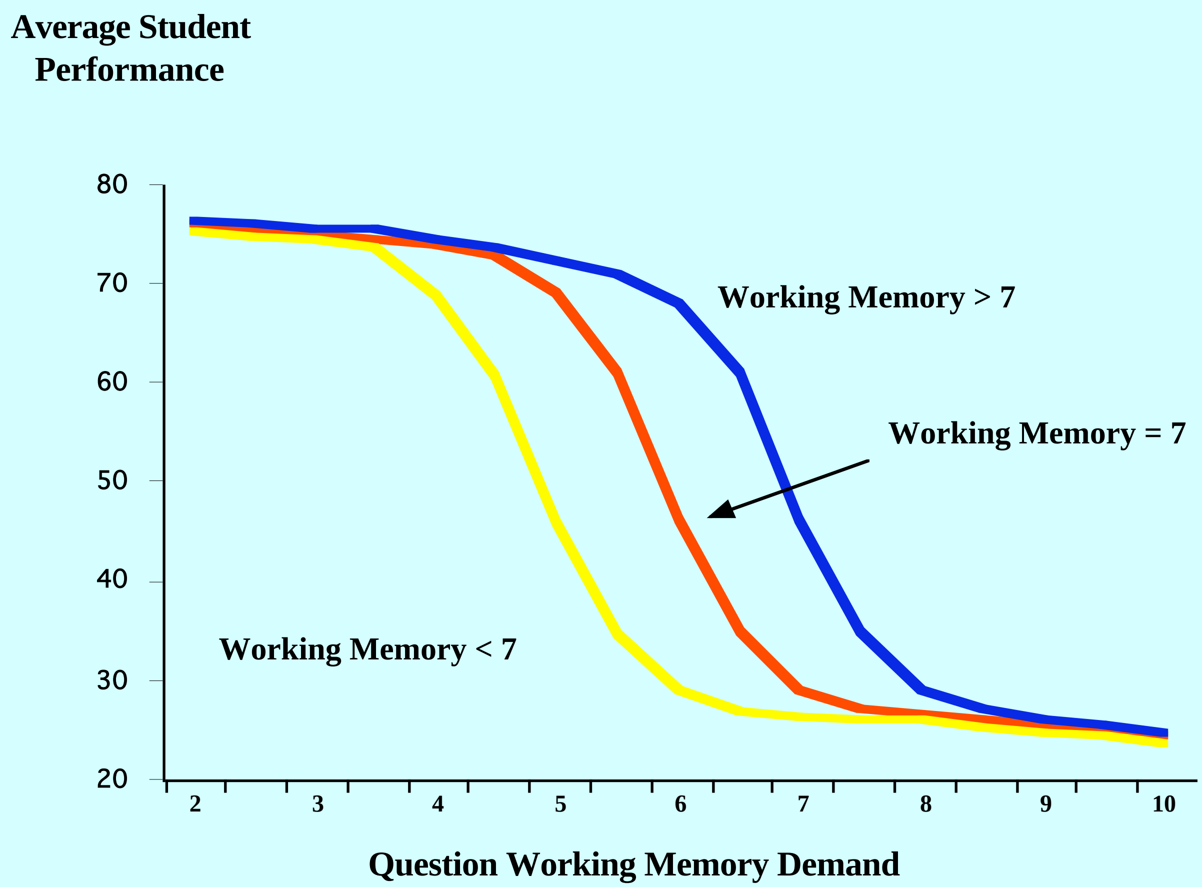
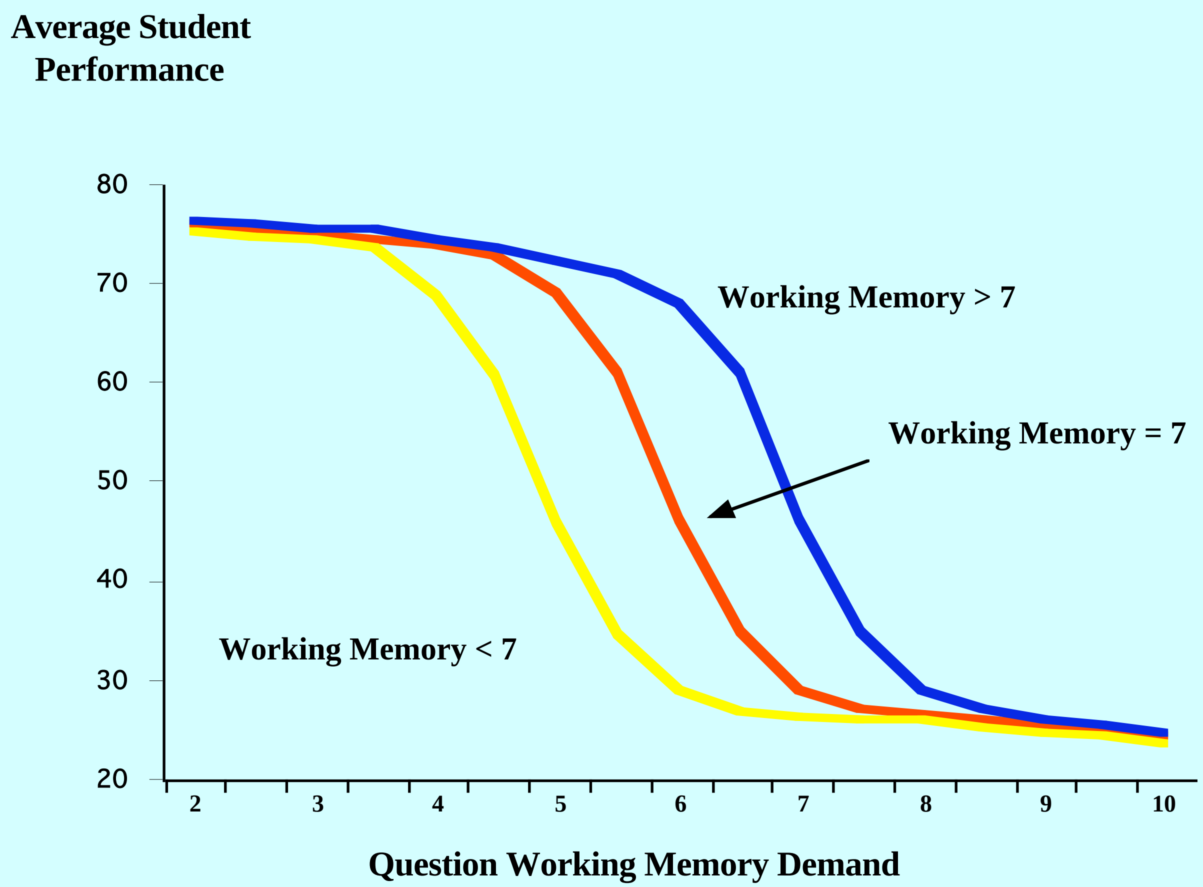
20
Sudden collapse in performance
2
3
4
5
6
7
8
9
10
Information Load

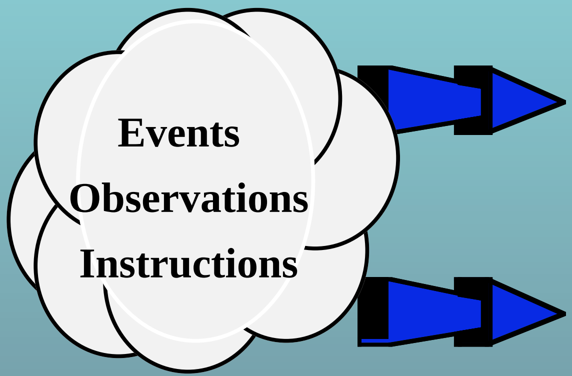

Average Student
Performance
80
70
60
50
40
30
20
2
3
4
5
6
7
8
9
10
Working Memory > 7
Working Memory = 7
Working Memory < 7
Question Working Memory Demand



Studies in Higher Education, 1989, 14(2), 159-168

An Information Processing Model

(based on empirical evidence)



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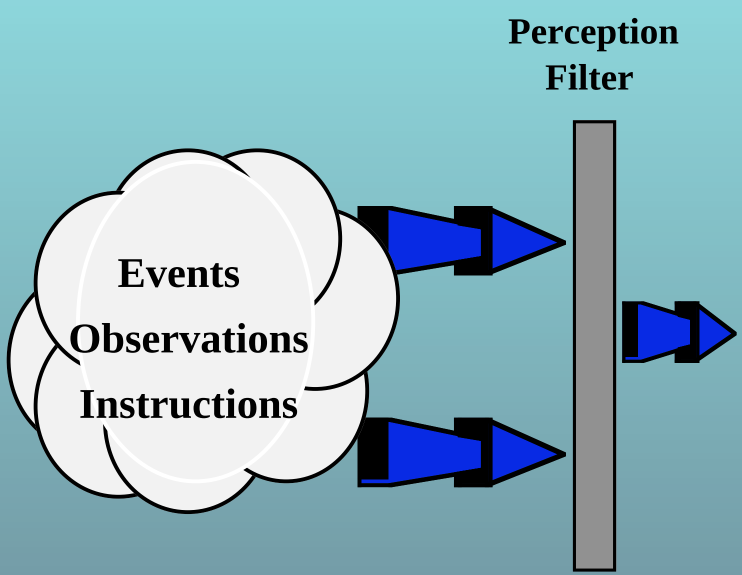

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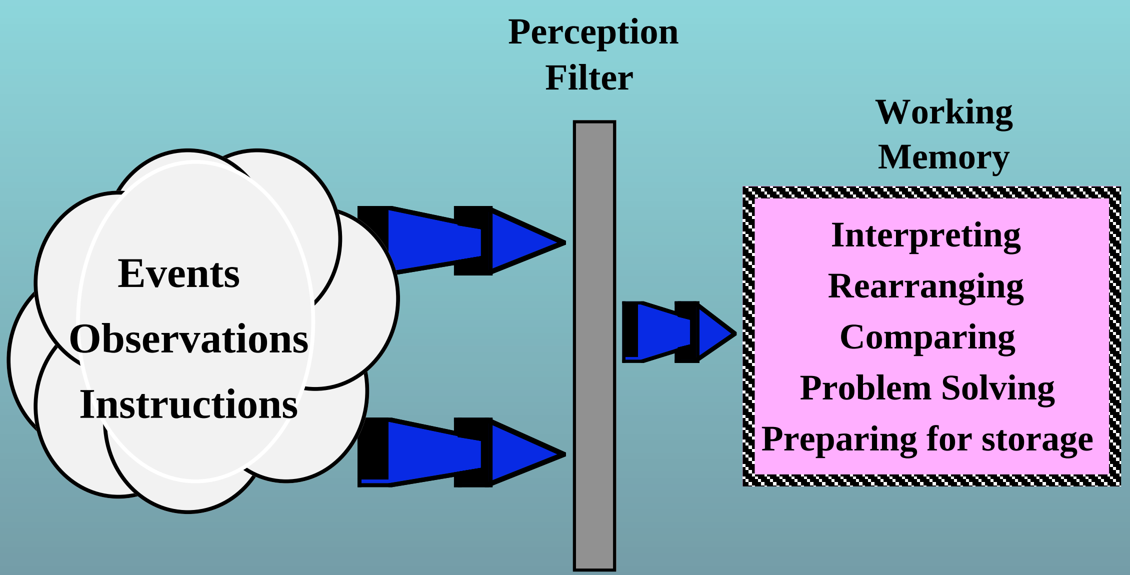

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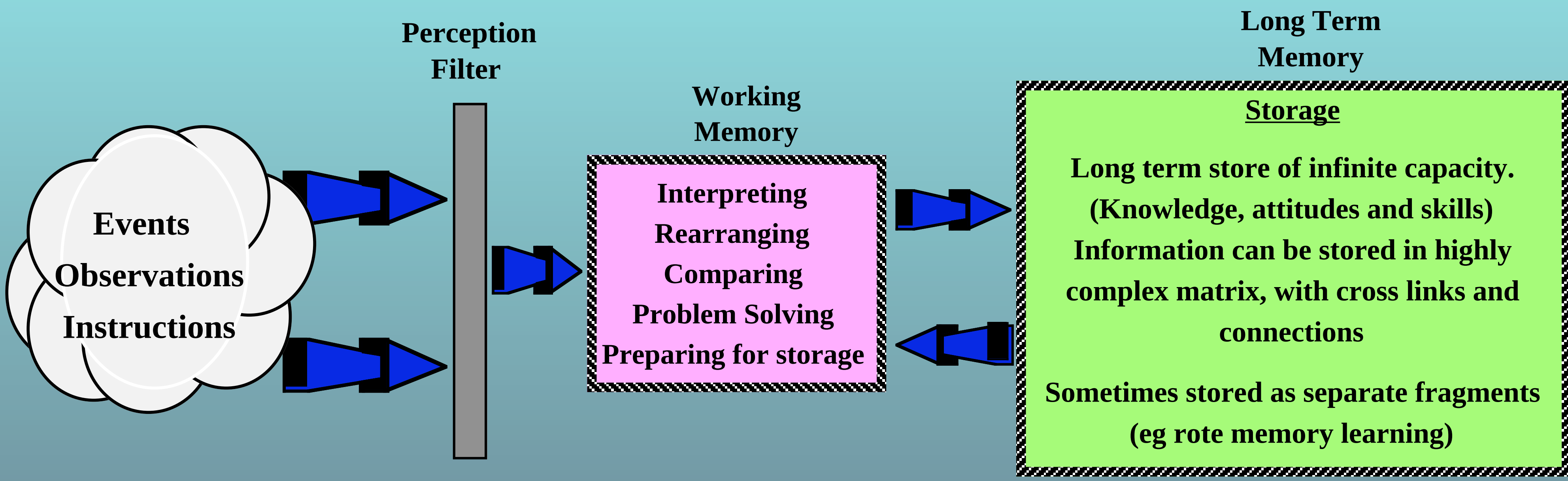

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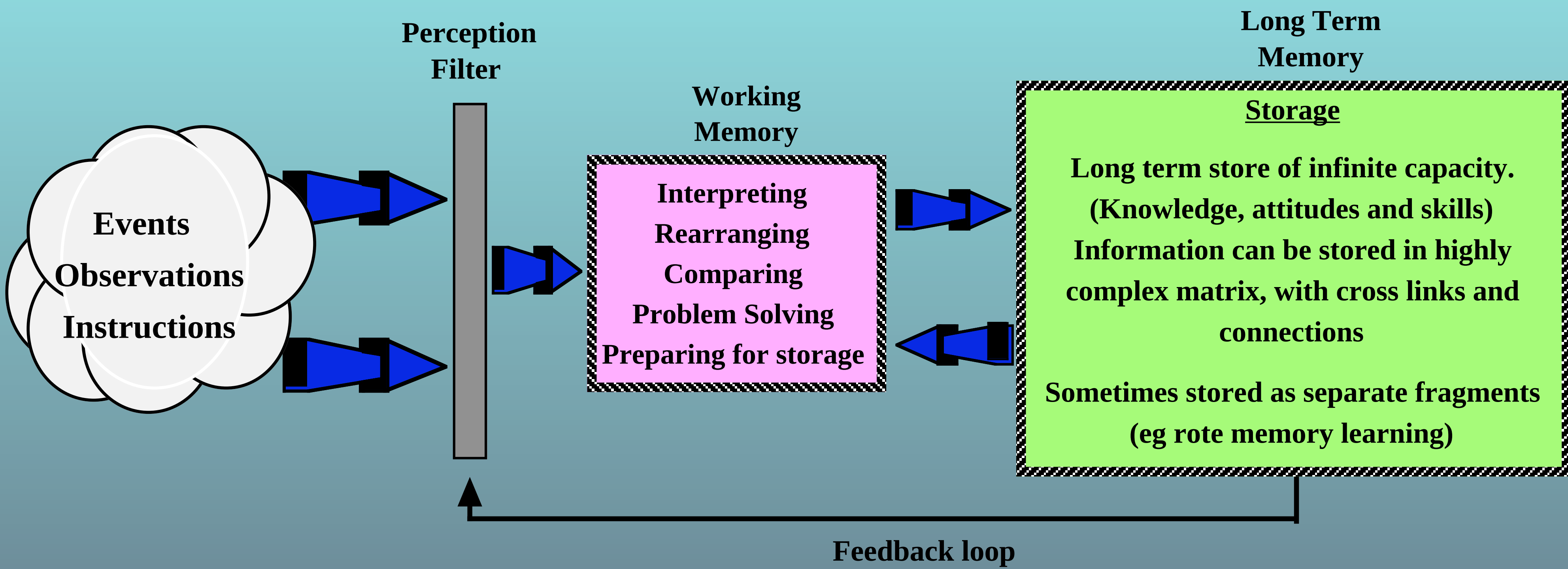

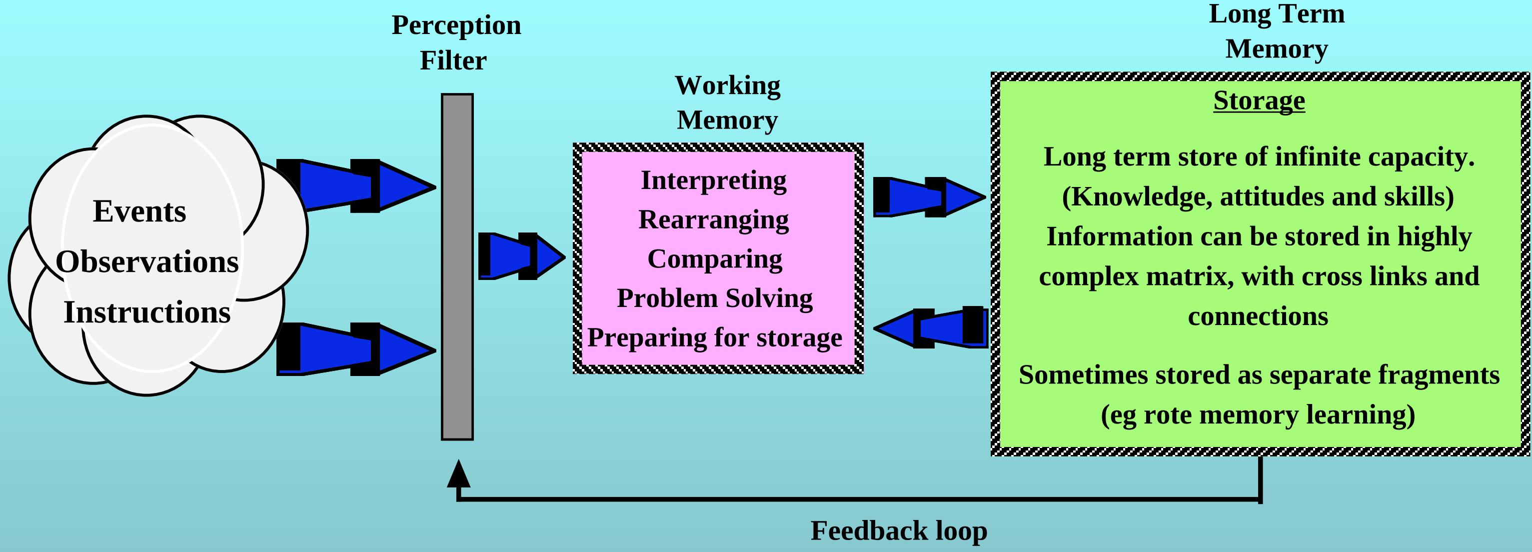
Perception
Filter
Working
Memory
Long Term
Memory
Events
Observations
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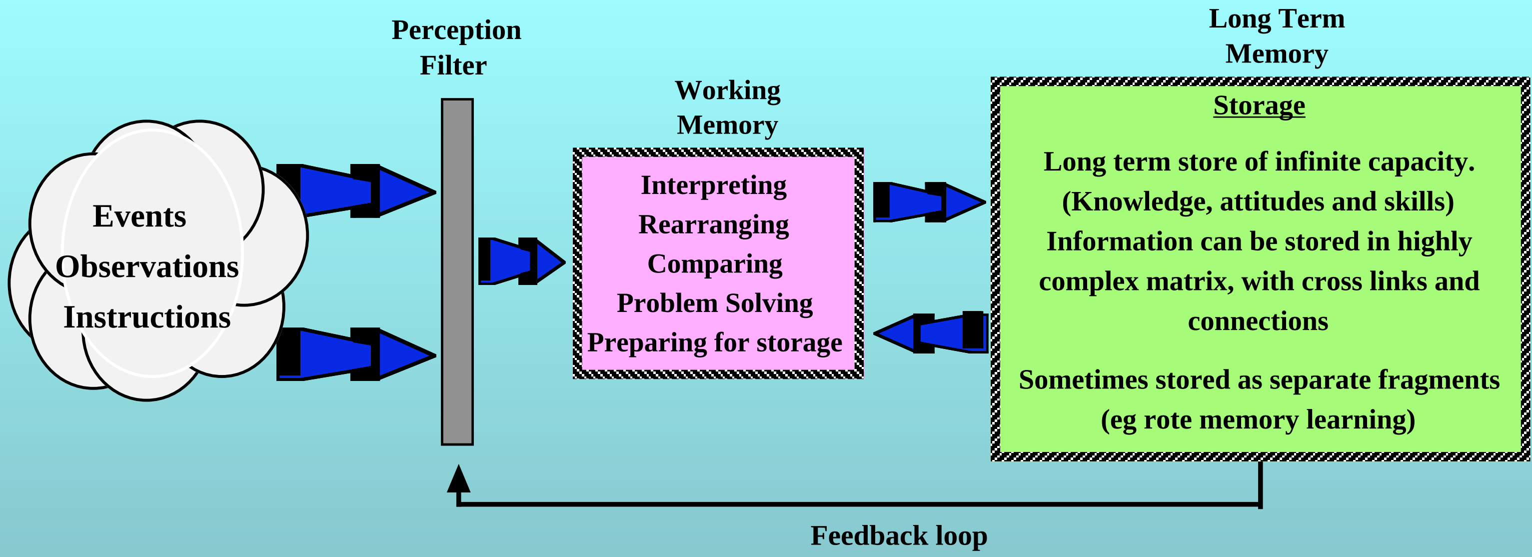
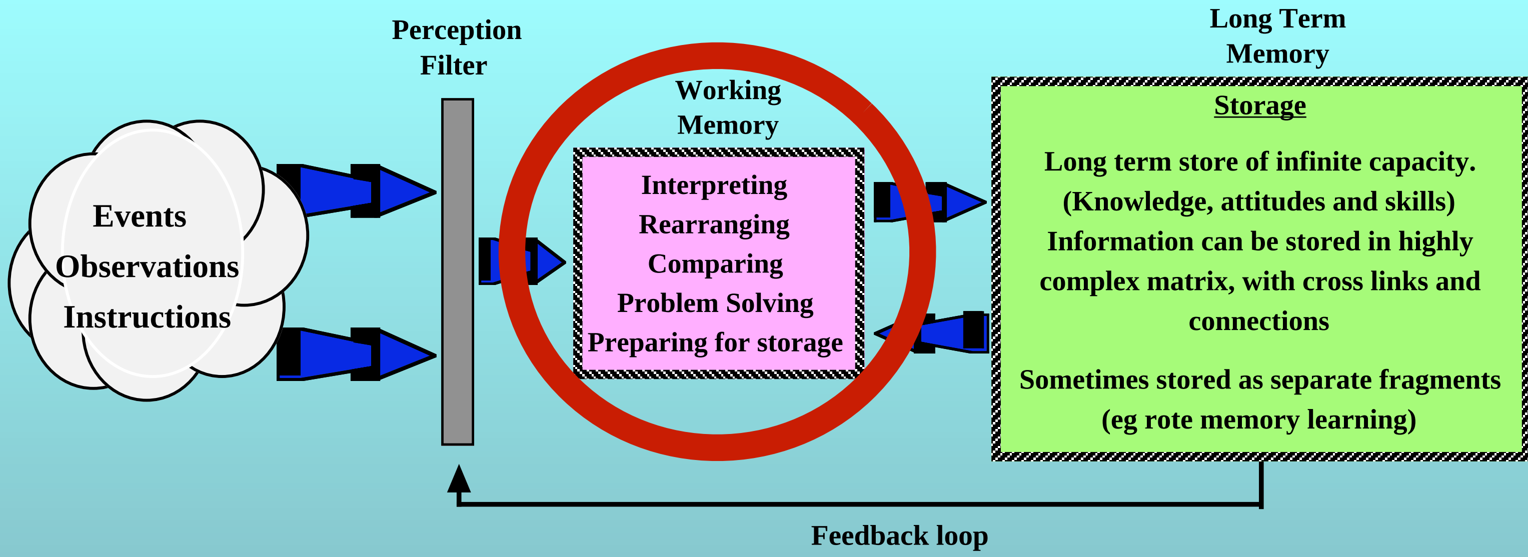
Storage
Long term store of infinite capacity.
(Knowledge, attitudes and skills)
Information can be stored in highly complex matrix, with cross links and connections
Sometimes stored as separate fragments
(eg rote memory learning)
Feedback loop



Predictions from the Model



Predictions from the Model

- If working memory is overloaded, learning will more or cease
- If the perception filter works efficiently, overload is less likely
- The filtration is controlled by what you know already
- If knowledge is stored in linked fashion, it will be more easily recalled

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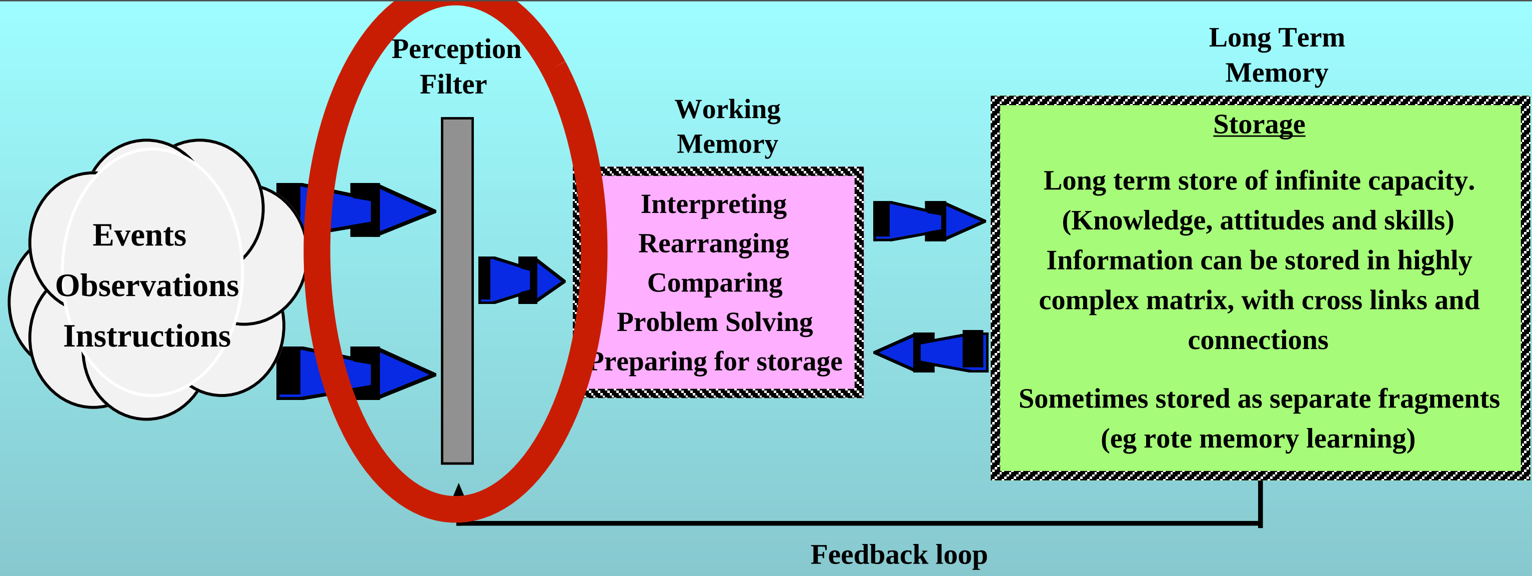

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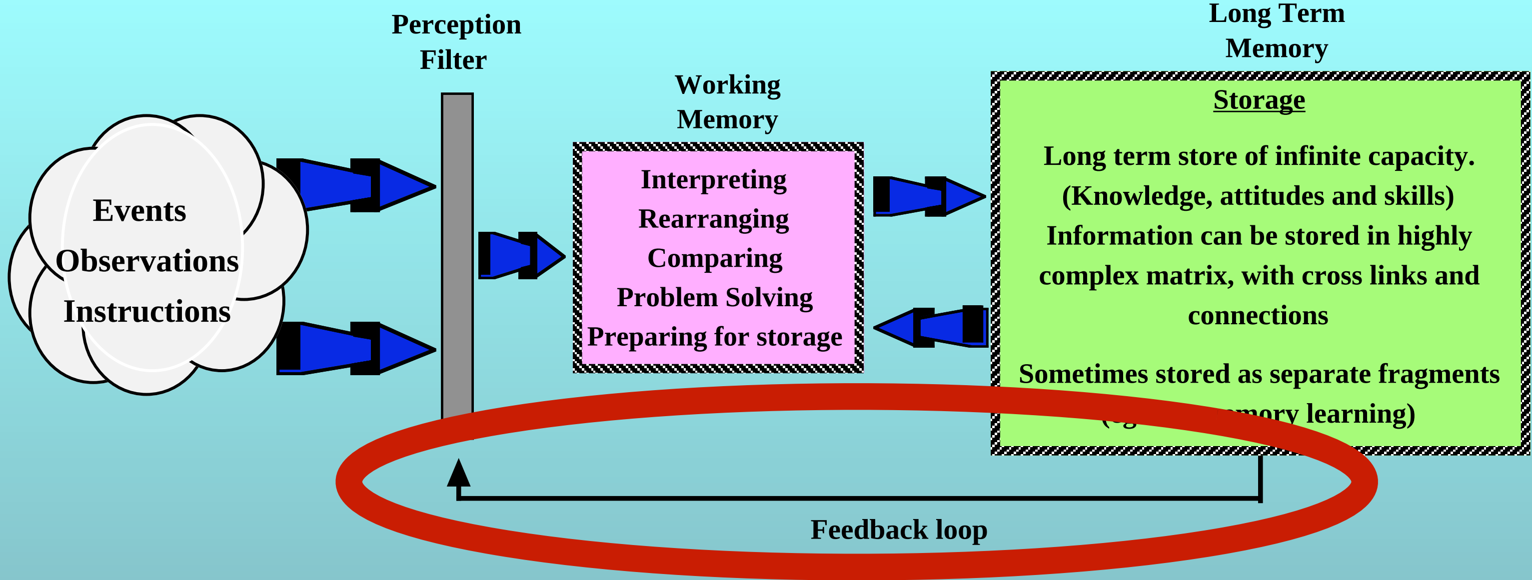

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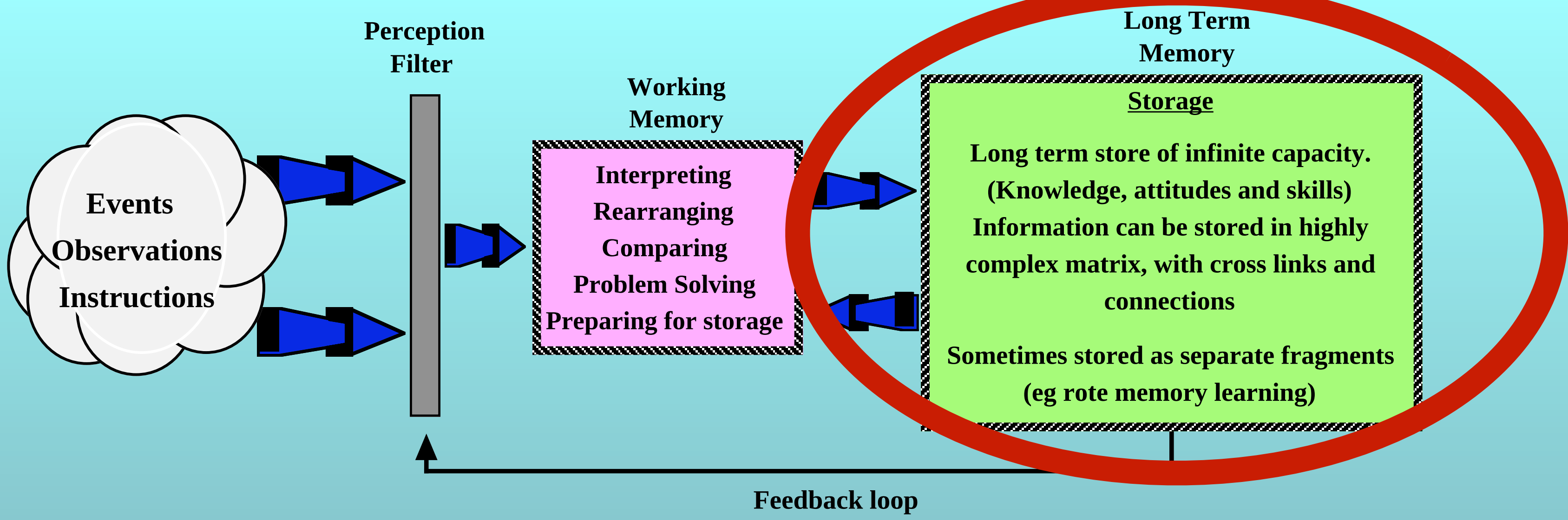

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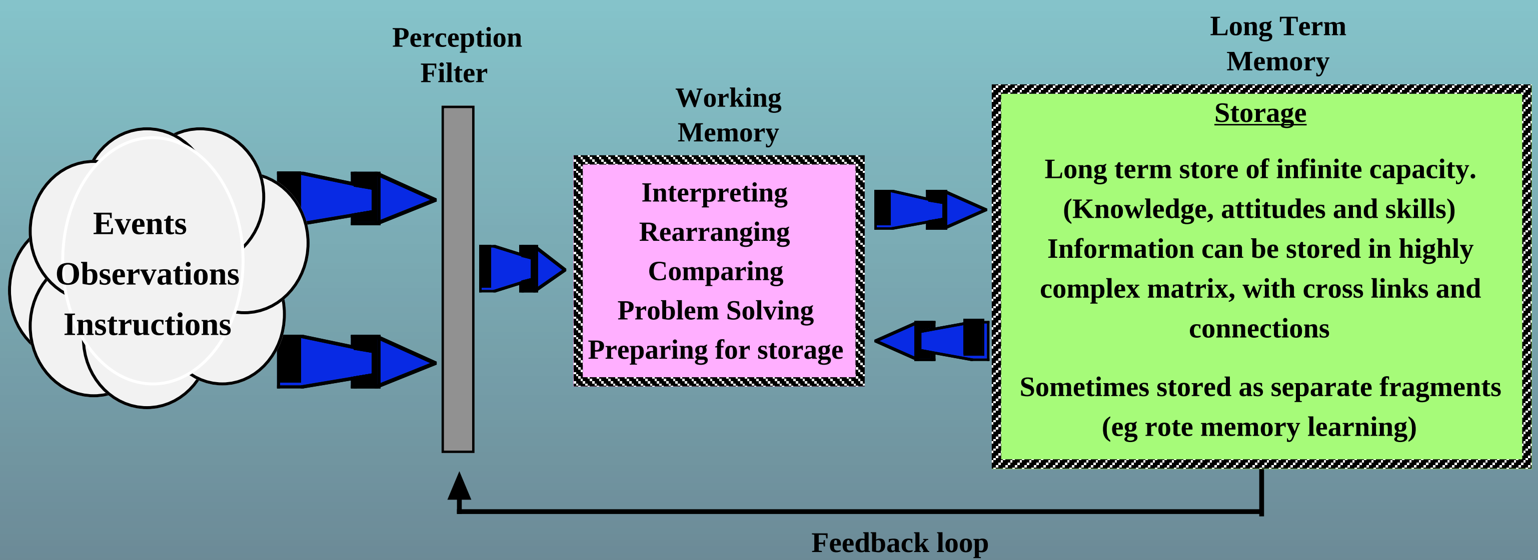
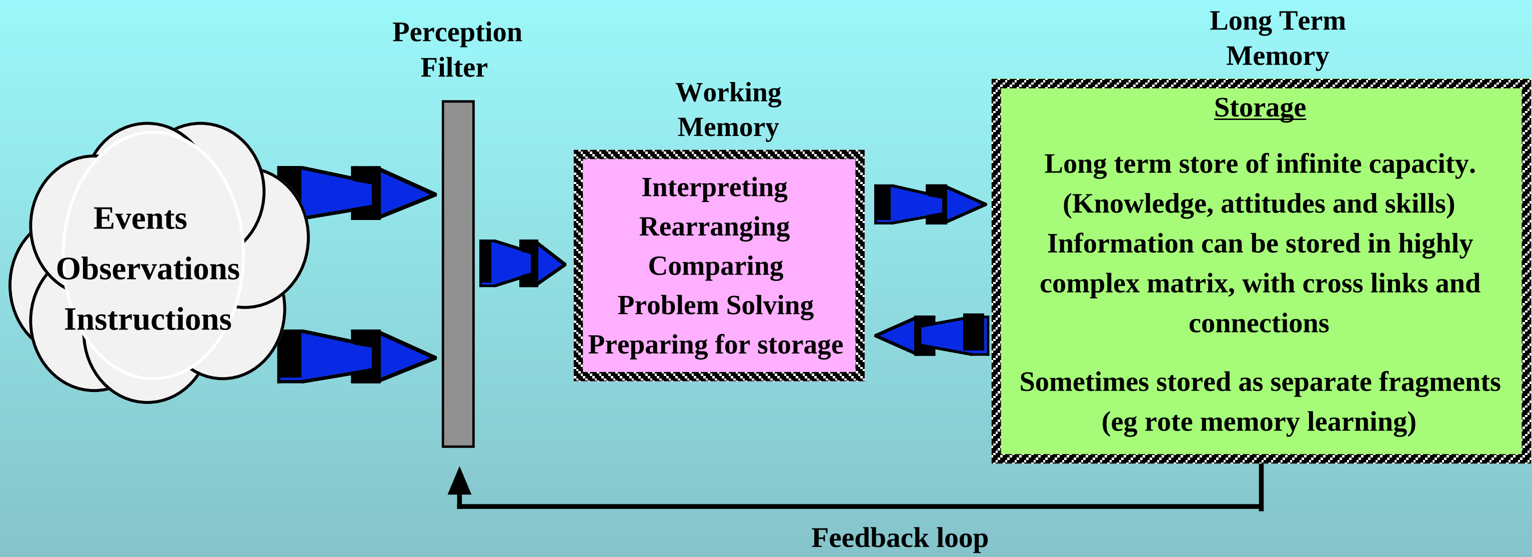
Learning

Everyone learns in essentially the same way
There are many variations in the details

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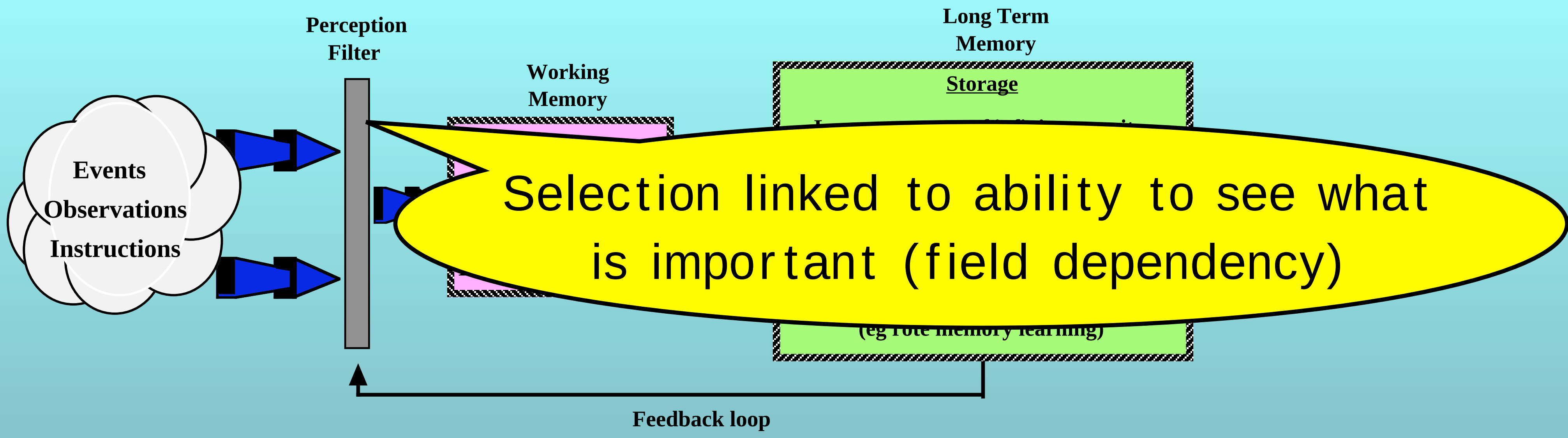
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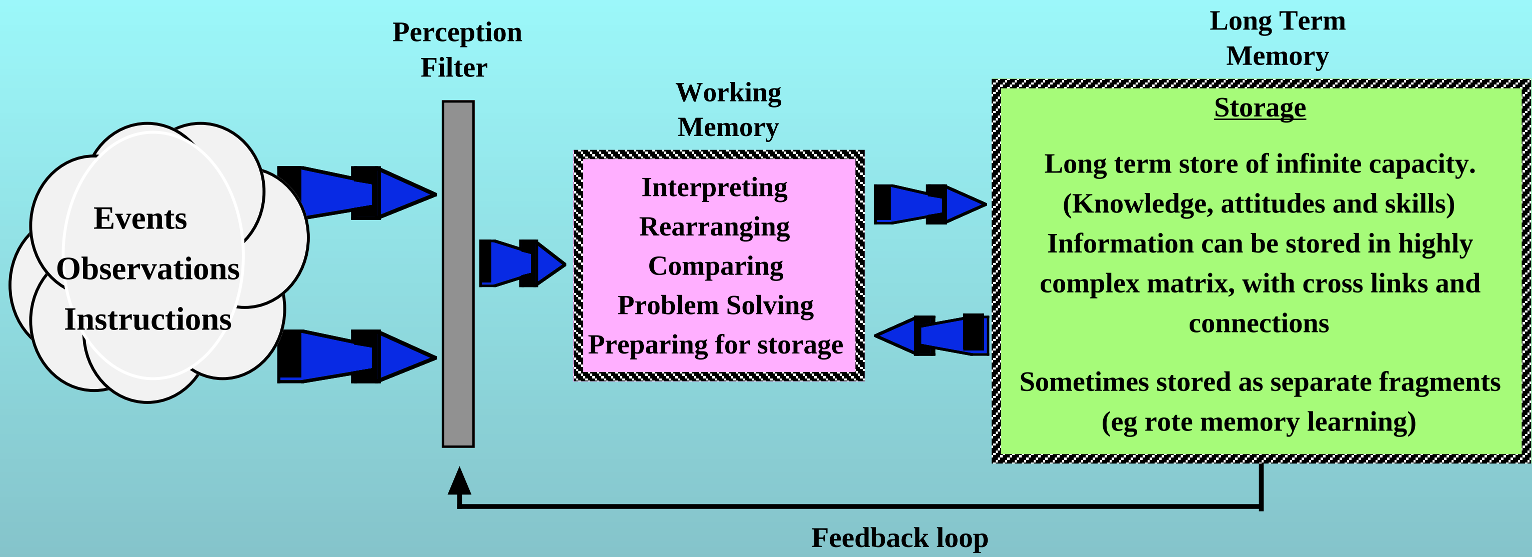
Selection linked to ability to see what is important (field dependency)
Feedback loop



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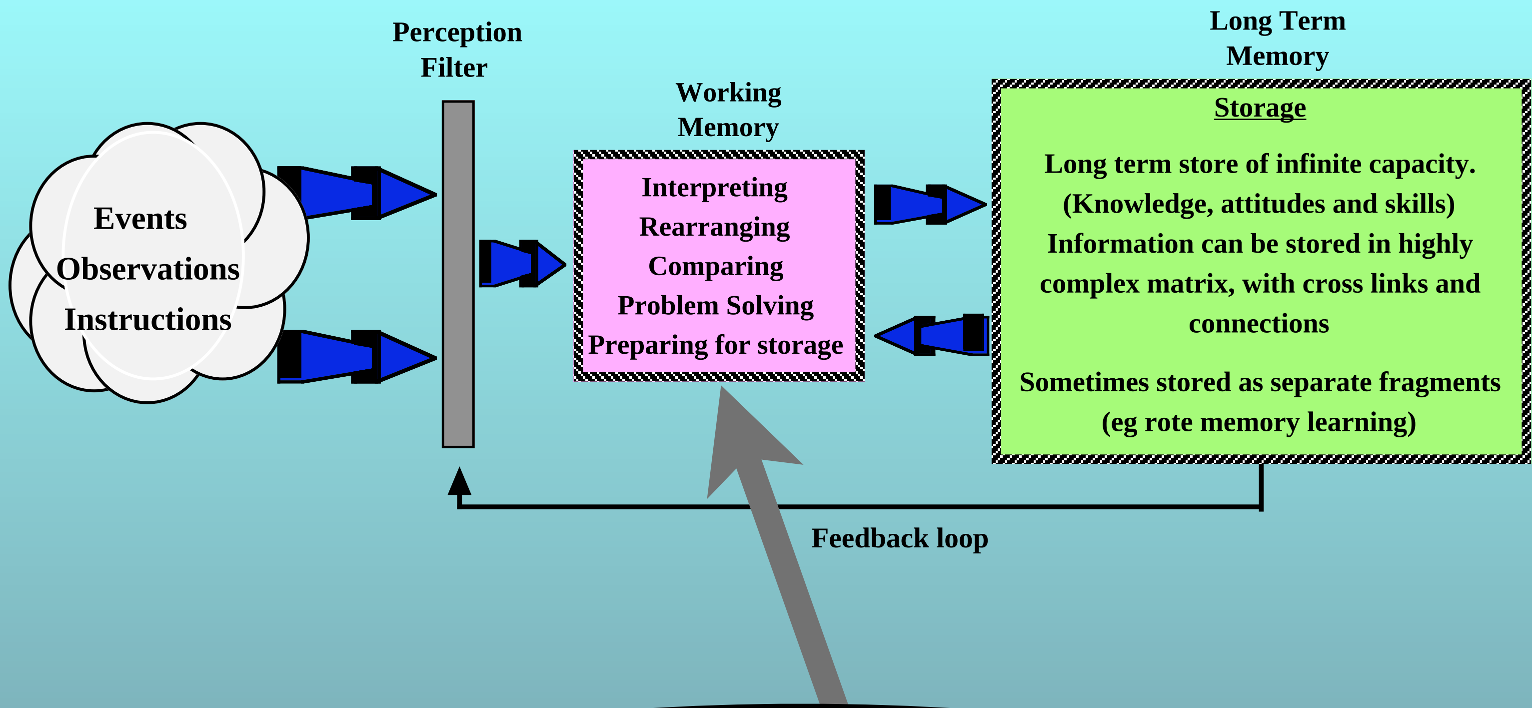
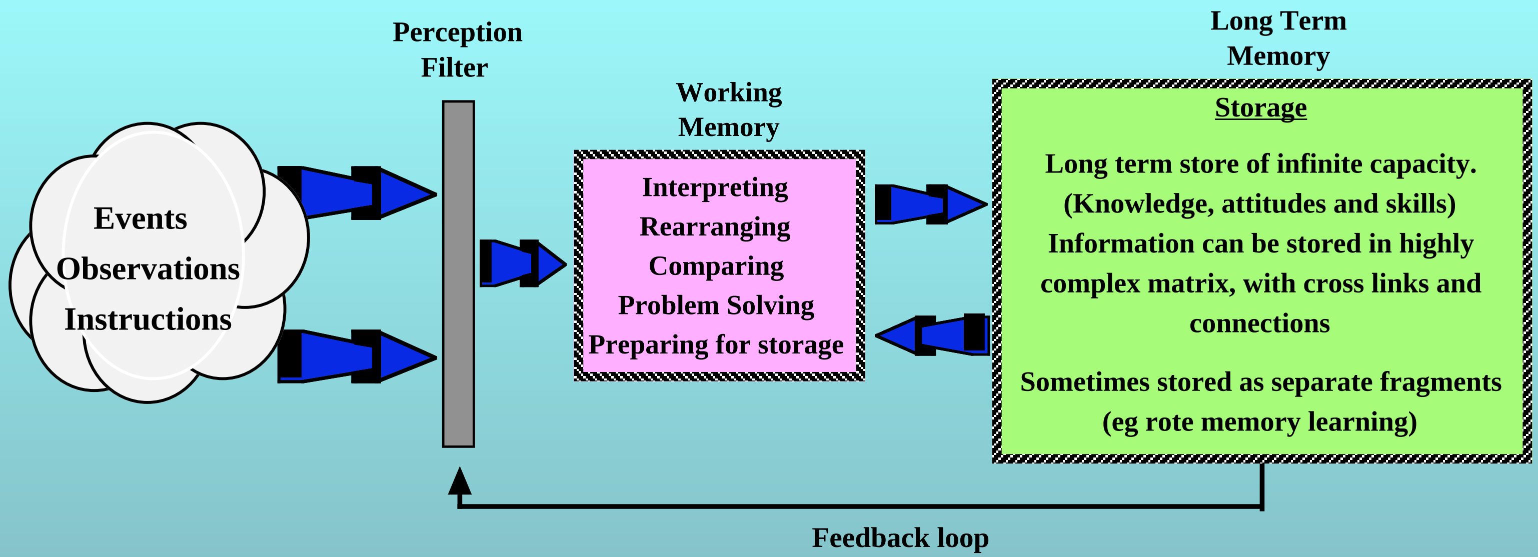


The working memory is of limited capacity (7±2)

Its capacity cannot be increased

It can be used more efficiently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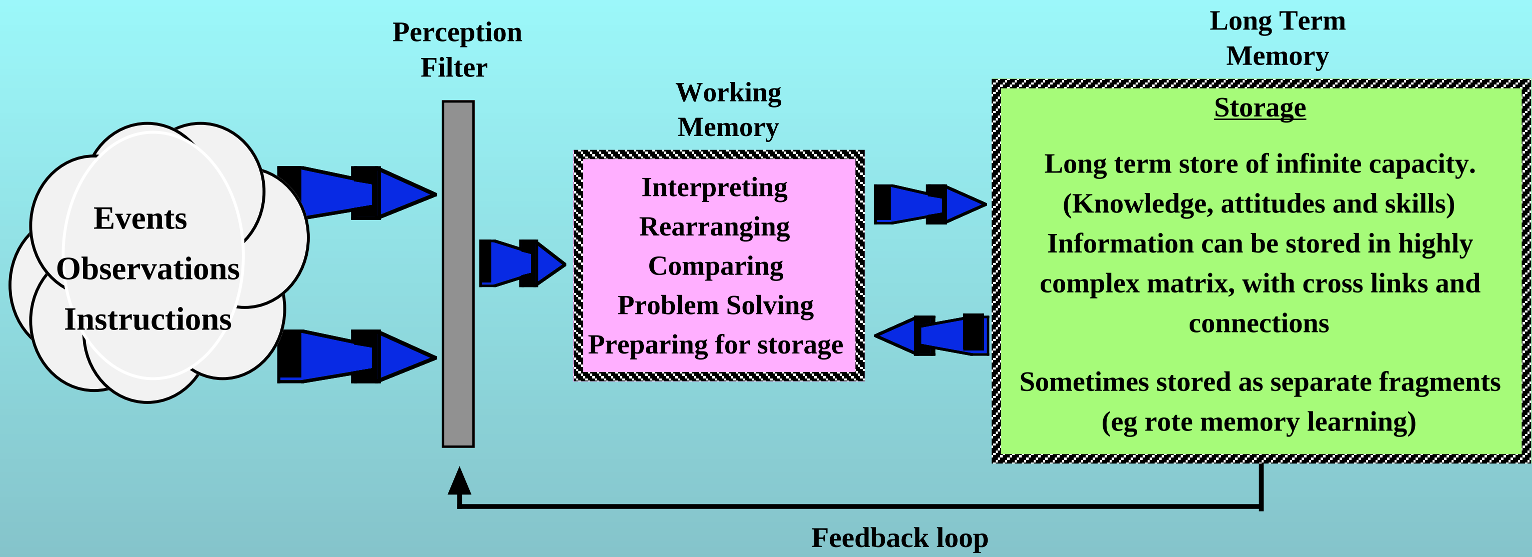
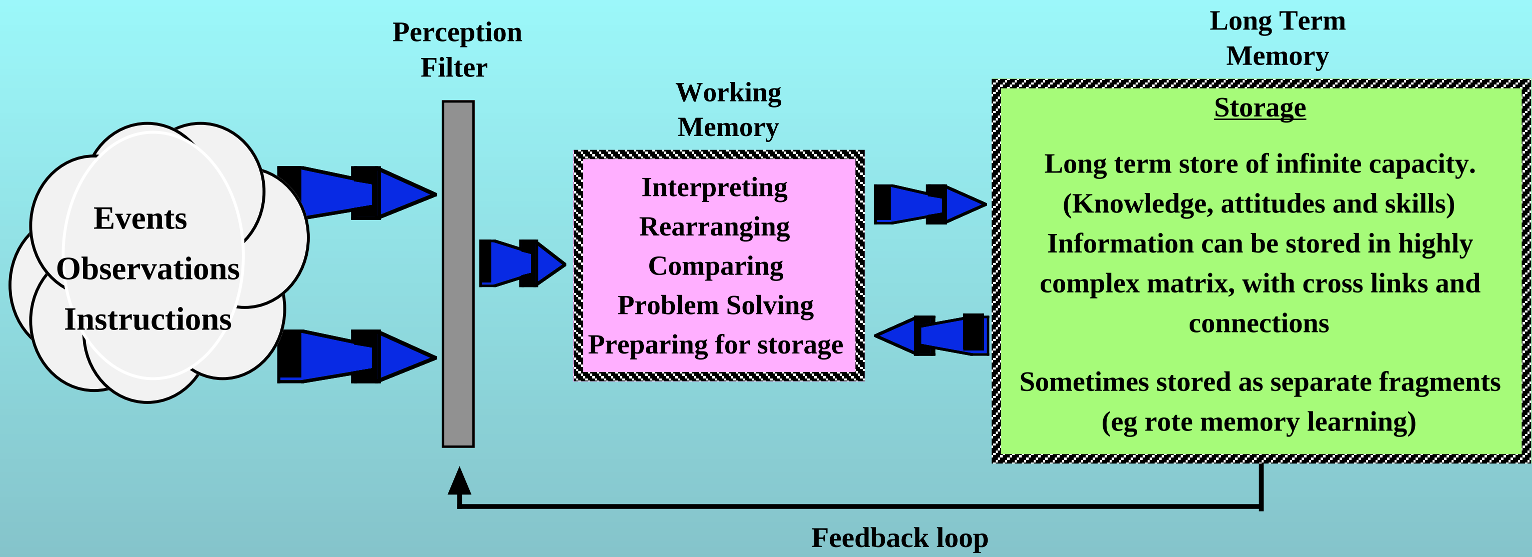


Selection based on previous knowledge, experience and attitudes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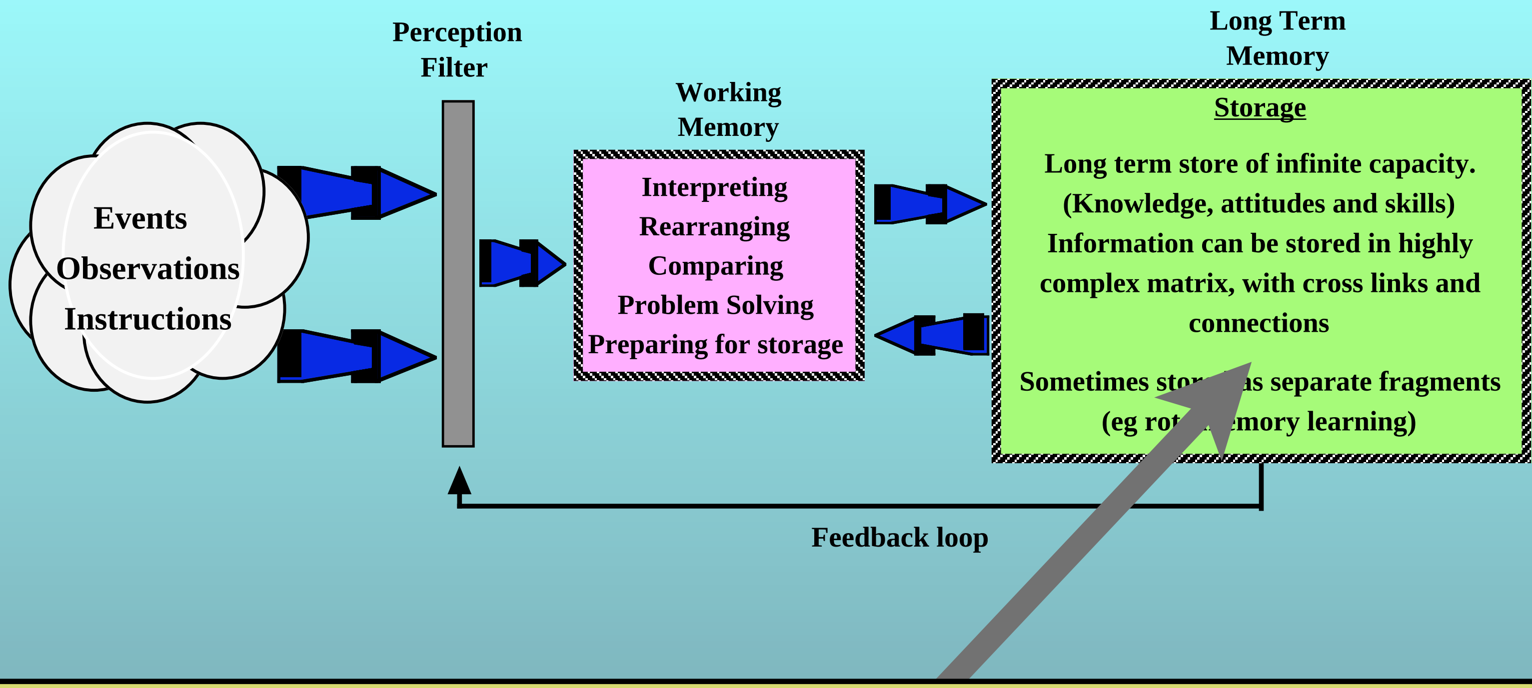

Students vary in the way they store information

- Extent of meaningful links between ideas
- Favoured storage: visually or symbolically
- Conceptual understanding related to links between ideas

The Idea of Pre-learning

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Watch the skilled school teacher

The Idea of Pre-learning

Watch the skilled school teacher

The idea of the Pre-lecture

The Idea of Pre-learning

Watch the skilled school teacher

The idea of the Pre-lecture

The idea of the Pre-laboratory

Preparing the Mind for Learning

First Year General Chemistry Class

Year	Pre-learning	Upper Group Average	Lower Group Average	Difference	Significance
1993-94	pre-lectures				
1994-95	pre-lectures				
1995-96	no pre-lectures				
1996-97	no pre-lectures				
1997-98	no pre-lectures				
1998-99	Chemorganisers				

Craig Gray and Ghassan Sirhan

University Chemistry Education, 1999, 5, 52-58.

Centre for Science Education, University of Glasgow, Scotland

Preparing the Mind for Learning

First Year General Chemistry Class					
Year	**Pre-learning**	**Upper Group Average**	**Lower Group Average**	**Difference**	**Significance**
1993-94	pre-lectures	50.9	48.8		
1994-95	pre-lectures	49.2	49.0		
1995-96	no pre-lectures	46.9	38.7		
1996-97	no pre-lectures	48.2	42.0		
1997-98	no pre-lectures	46.7	41.3		
1998-99	Chemorganisers	49.8	47.7		

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Preparing the Mind for Learning

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Year	Pre-learning	Upper Group Average	Lower Group Average	Difference	Significance
1993-94	pre-lectures	50.9	48.8	2.1	not sig
1994-95	pre-lectures	49.2	49.0	0.2	not sig
1995-96	no pre-lectures	46.9	38.7	8.2	sig
1996-97	no pre-lectures	48.2	42.0	6.2	sig
1997-98	no pre-lectures	46.7	41.3	5.4	sig
1998-99	Chemorganisers	49.8	47.7	2.1	not sig

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University Chemistry Education, 1999, 5, 52-58.

Physics Laboratories

What Was Done

Four Experiments

Each student did two of them with pre-laboratory exercises and two without.

Combinations were varied.

Each student was assessed on learning by two means:

Traditional demonstrator marked performance
Post-laboratory exercises, testing understanding and application of ideas.

Student attitudes were assessed.

Physics Laboratories

What was Found

Pre-laboratories increased performance on student marking by around 5%

Pre-laboratories increased performance on exercises by around 11%

Students were dramatically more positive about pre-laboratories

Physics Education (1998) 33(1) , 22-29

First Year Chemistry Laboratories

What was done

Four Groups of Students (N = 500)

Group 1	Control
Group 2	Pre-laboratory exercises used
Group 3	Mini-project used
Group 4	Pre-laboratory plus miniproject

Understanding checked by looking at questions asked
Attitudes measured

First Year Chemistry Laboratories

What was found

First Year Chemistry Laboratories

What was found

		Questions asked
Group 1	Control	121
Group 2	Pre-laboratory exercises used	58
Group 3	Mini-project used	145
Group 4	Pre-laboratory and miniproject	64

First Year Chemistry Laboratories

What was found

		Questions asked
Group 1	Control	121
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Studies in Higher Education, 1994, 19(1), 77-88.

First Year Chemistry Laboratories

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Studies in Higher Education, 1994, 19(1), 77-88.

Enhancing Chemistry Laboratories, RSC

Reducing the Load on Working Memory

Reducing the Load on Working Memory

This must NOT involve:

Changing what is to be taught

Changing the time demand

Simply avoiding problem areas

Massive re-training of lecturers/teachers

Reducing the Load on Working Memory

Reducing the Load on Working Memory

It may involve:

Changing the teaching order
Modifying speed and sequencing
Breaking down complex areas
Allowing learning to fit human psychology

Can We Reduce the Load on Working Memory?

The work of Eleni Danili in Greece

Can We Reduce the Load on Working Memory?

The work of Eleni Danili in Greece

- She measured the working memory capacity of the students and also their ability to ‘see the message from the noise’.

Can We Reduce the Load on Working Memory?

The work of Eleni Danili in Greece

- She measured the working memory capacity of the students and also their ability to ‘see the message from the noise’.
- She re-designed a large section of chemistry teaching at school level, specifically to reduce working memory overload problems.

Performance Depends on ....

- Working Memory Capacity
- Field dependency (seeing the ‘message’ amidst the ‘noise’)

Performance Depends on ....

- **Working Memory Capacity**
- **Field dependency (seeing the ‘message’ amidst the ‘noise’)**

Performance (%)			
N = 105	-	field dependency	+
w.m. $\leq$ 5			
w.m. = 6			
w.m. $\geq$ 7			

Performance Depends on ....

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Performance (%)			
N = 105	-	field dependency	+
w.m. ≤ 5		54	
w.m. = 6		60	
w.m. ≥ 7		69	

Performance Depends on ....

- **Working Memory Capacity**
- **Field dependency (seeing the 'message' amidst the 'noise')**

Performance (%)			
N = 105	-	field dependency	+
w.m. $\leq$ 5			
w.m. = 6	46	60	72
w.m. $\geq$ 7			

Performance Depends on ....

- **Working Memory Capacity**
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Performance (%)			
N = 105	- field dependency +		
w.m. ≤ 5	47	54	59
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Performance Improvement

Using Control and Experimental Groups
(pre and post tests)

Performance Improvement

Using Control and Experimental Groups
(pre and post tests)

Normal Teaching

Performance Improvement

Using Control and Experimental Groups
(pre and post tests)

Normal Teaching

Reduce working memory demand

Performance Improvement

Using Control and Experimental Groups
(pre and post tests)

Normal Teaching

Reduce working memory demand

N = 211	Performance Improvement
Control Group	
Experimental Group	

Performance Improvement

Using Control and Experimental Groups
(pre and post tests)

Normal Teaching

Reduce working memory demand

N = 211	Performance Improvement
Control Group	13%
Experimental Group	

Performance Improvement

Using Control and Experimental Groups
(pre and post tests)

Normal Teaching

Reduce working
memory demand

N = 211	Performance Improvement
Control Group	13%
Experimental Group	22%

A Larger Experiment

(800 Senior School Students)

Furat Hussein in the Emirates

A Larger Experiment

(800 Senior School Students)

Testing Two Hypotheses

1. Reducing load on working memory will bring improved understanding.
2. Use appropriate applications and interaction will enhance attitudes

Furat Hussein in the Emirates

A Larger Experiment

(800 Senior School Students)

Testing Two Hypotheses

1. Reducing load on working memory will bring improved understanding.
2. Use appropriate applications and interaction will enhance attitudes

* Minimise working memory overload;
* Use relevant applications;
* Encourage understanding not memorising;
* Link new material to previously taught material in a meaningful way

Furat Hussein in the Emirates

Experimental Structure

Experimental Structure

Time →

Group 1 *(200 students)*	**Periodic Table** *(Booklet)*	↑	**Chemical Equations** *(normal teaching)*	↑
Group 2 *(200 students)*	**Periodic Table** *(normal teaching)*	**Assessment**	**Chemical Equations** *(Booklet)*	**Assessment**

Experimental Structure

Time →

Group 1 *(200 students)*	**Periodic Table** *(Booklet)*		**Chemical Equations** *(normal teaching)*	
Group 2 *(200 students)*	**Periodic Table** *(normal teaching)*		**Chemical Equations** *(Booklet)*	
		Assessment		**Assessment**

Time →

Group 1 *(200 students)*	**Organic Chemistry** *(Booklet)*		**Acids and Alkalis** *(normal teaching)*	
Group 2 *(200 students)*	**Organic Chemistry** *(normal teaching)*		**Acids and Alkalis** *(Booklet)*	
		Assessment		**Assessment**

Performance Data

N = 800	Mean (%)	Gain	t-test	Probability
Periodic Table (Year 10)				
Experimental Group				
Control Group				
Chemical Equations (Year 10)				
Experimental Group				
Control Group				
Organic (Year 11)				
Experimental Group				
Control Group				
Acids and Alkalis (Year 11)				
Experimental Group				
Control Group				

Performance Data

N = 800	Mean (%)	Gain	t-test	Probability
Periodic Table (Year 10)				
Experimental Group	79.2	18.2	26.2	$p < 0.001$
Control Group	61.0			
Chemical Equations (Year 10)				
Experimental Group				
Control Group				
Organic (Year 11)				
Experimental Group				
Control Group				
Acids and Alkalis (Year 11)				
Experimental Group				
Control Group				

Performance Data

N = 800	Mean (%)	Gain	t-test	Probability
Periodic Table (Year 10)				
Experimental Group	79.2	18.2	26.2	$p < 0.001$
Control Group	61.0			
Chemical Equations (Year 10)				
Experimental Group	80.2	9.2	9.7	$p < 0.001$
Control Group	71.0			
Organic (Year 11)				
Experimental Group				
Control Group				
Acids and Alkalis (Year 11)				
Experimental Group				
Control Group				

Performance Data

N = 800	Mean (%)	Gain	t-test	Probability
Periodic Table (Year 10)				
Experimental Group	79.2	18.2	26.2	$p < 0.001$
Control Group	61.0			
Chemical Equations (Year 10)				
Experimental Group	80.2	9.2	9.7	$p < 0.001$
Control Group	71.0			
Organic (Year 11)				
Experimental Group	71.0	14.0	19.7	$p < 0.001$
Control Group	57.0			
Acids and Alkalis (Year 11)				
Experimental Group				
Control Group				

Performance Data

N = 800	Mean (%)	Gain	t-test	Probability
Periodic Table (Year 10)				
Experimental Group	79.2	18.2	26.2	$p < 0.001$
Control Group	61.0			
Chemical Equations (Year 10)				
Experimental Group	80.2	9.2	9.7	$p < 0.001$
Control Group	71.0			
Organic (Year 11)				
Experimental Group	71.0	14.0	19.7	$p < 0.001$
Control Group	57.0			
Acids and Alkalis (Year 11)				
Experimental Group	75.0	10.7	15.1	$p < 0.001$
Control Group	64.3			

Some Attitude Changes

								χ^2
I like chemistry lessons	40	17	11	10	12	10	*I hate chemistry lessons*	
	70	10	3	2	3	12		36.7 ($p < 0.001$)
Boring	17	9	11	14	20	29	*Interesting*	
	20	1	1	2	5	71		66.0 ($p < 0.001$)
Easy	19	21	16	7	11	26	*Difficult*	
	60	9	1	4	1	25		47.1 ($p < 0.001$)
Useless	8	4	5	8	13	62	*Useful*	
	10	8	2	2	5	73		14.1 ($p < 0.001$)
Important	60	10	10	4	8	8	*Unimportant*	
	69	11	2	3	6	9		13.2 ($p < 0.001$)
Enjoyable	18	17	18	16	8	2	*Boring*	
	66	12	1	1	3	17		104.1 ($p < 0.001$)
Control Group		N =	115					
Experimental Group		N =	400					

Some Attitude Changes

								χ^2
I like chemistry lessons	40	17	11	10	12	10	*I hate chemistry lessons*	
	70	10	3	2	3	12		36.7 ($p < 0.001$)
Boring	17	9	11	14	20	29	*Interesting*	
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Control Group		N =	115					
Experimental Group		N =	400					

More Attitude Changes

								χ^2
I am enjoying the subject	15	24	13	25	9	14	*I am NOT enjoying the subject*	
	66	6	2	2	5	19		104.2($p < 0.001$)
I feel I am NOT coping well	18	10	11	10	24	27	*I feel I am coping well*	
	30	10	11	3	7	39		39.6 ($p < 0.001$)
I find it very easy	22	27	23	16	8	4	*find it very hard*	
	67	4	3	2	2	22		129.0 ($p < 0.001$)
I am NOT obtaining	6	12	12	12	24	34	*I am obtaining a lot of new skills*	
a lot of new skills	5	9	10	9	12	55		19.6 ($p < 0.001$)
I am getting better	35	23	15	12	9	6	*I am getting worse in the subject*	
in the subject	68	6	2	1	7	16		67.5 ($p < 0.001$)
It is definitely 'my' subject	15	23	29	18	10	5	*It is definitely not 'my' subject*	
	35	9	14	20	20	2		31.1 ($p < 0.01$)

Control Group		N =	115
Experimental Group		N =	400

More Attitude Changes

								χ^2
I am enjoying the subject	15	24	13	25	9	14	*I am NOT enjoying the subject*	
	66	6	2	2	5	19		104.2($p < 0.001$)
I feel I am NOT coping well	18	10	11	10	24	27	*I feel I am coping well*	
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I am NOT obtaining	6	12	12	12	24	34	*I am obtaining a lot of new skills*	
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Control Group		N =	115
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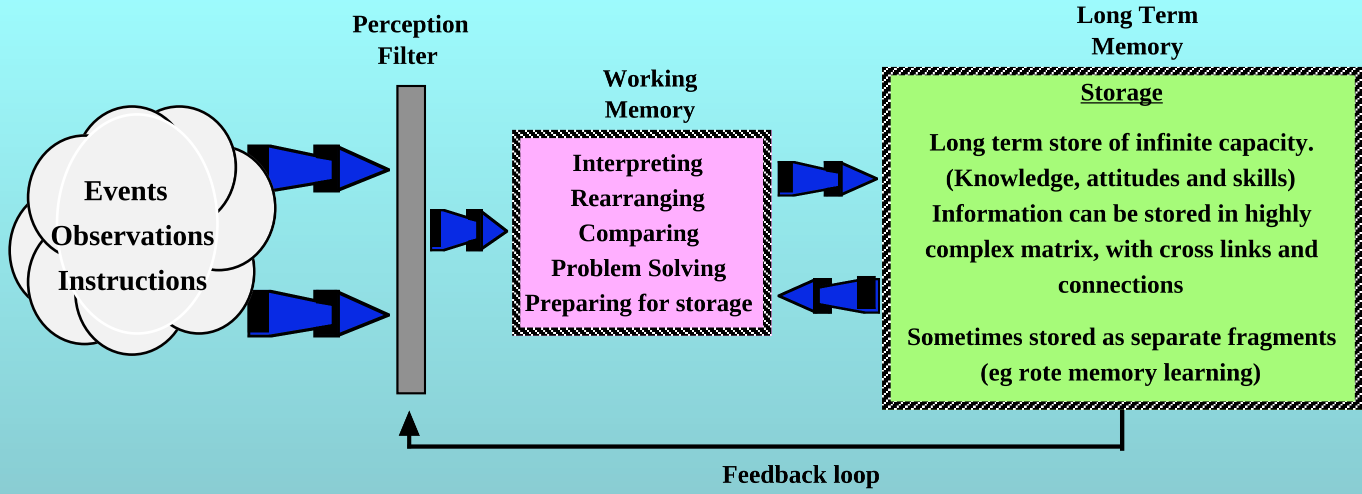
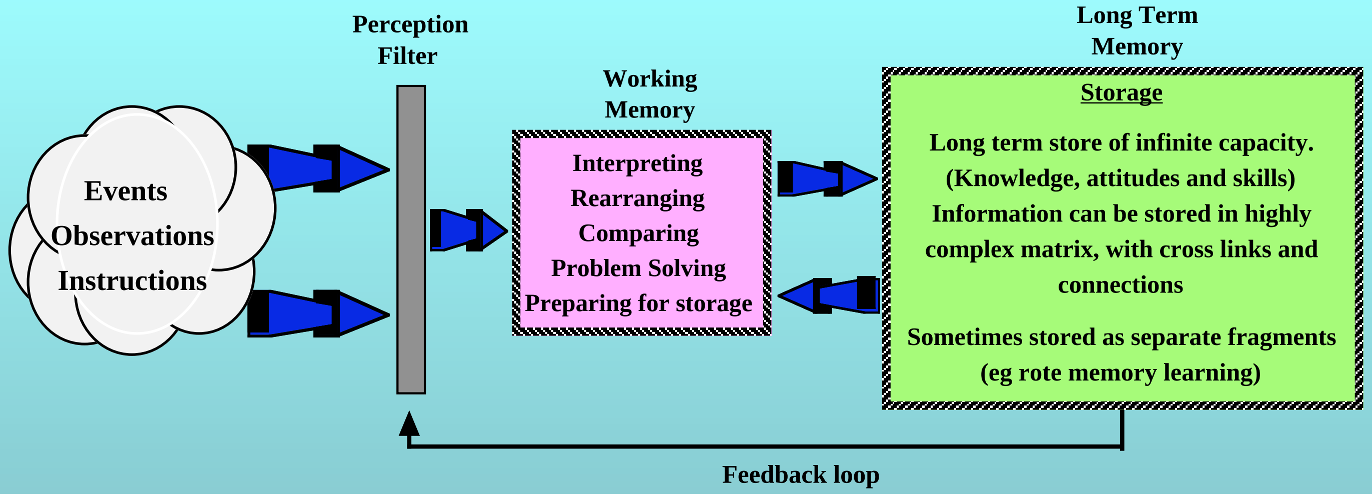
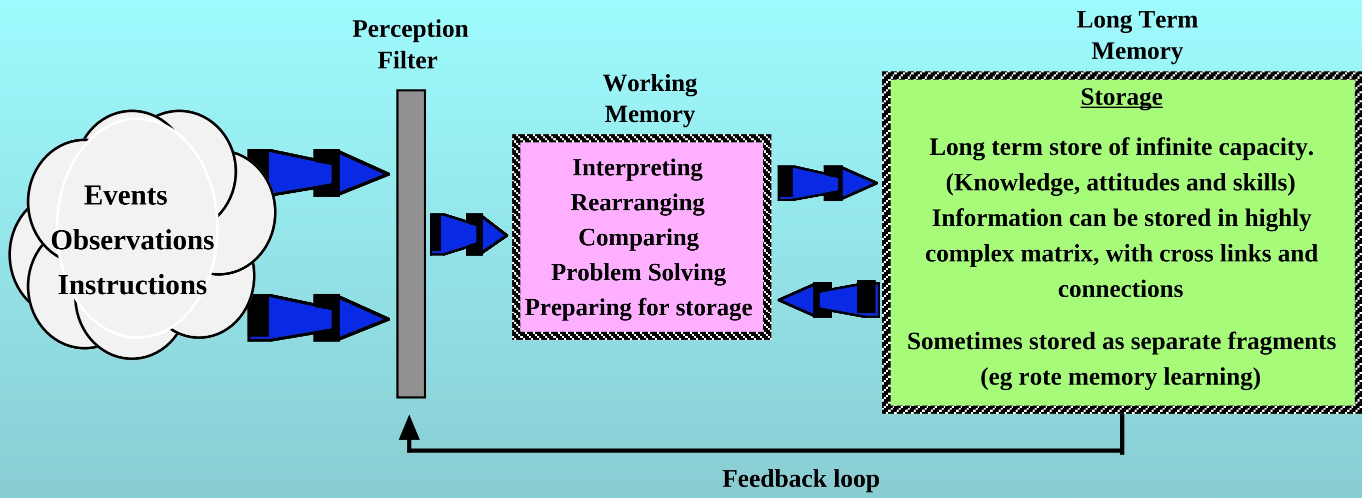

Perception Filter
Working Memory
Long Term Memory
Events
Observations
Instructions
Interpreting
Rearranging
Comparing
Problem Solving
Preparing for storage
Storage
Long term store of infinite capacity.
(Knowledge, attitudes and skills)
Information can be stored in highly complex matrix, with cross links and connections
Sometimes stored as separate fragments
(eg rote memory learning)
Feedback loop



- Improve Selection
- Lower Working Memory demand
- Encourage Understanding



Pre-learning

- Improve Selection
- Lower Working Memory demand
- Encourage Understanding

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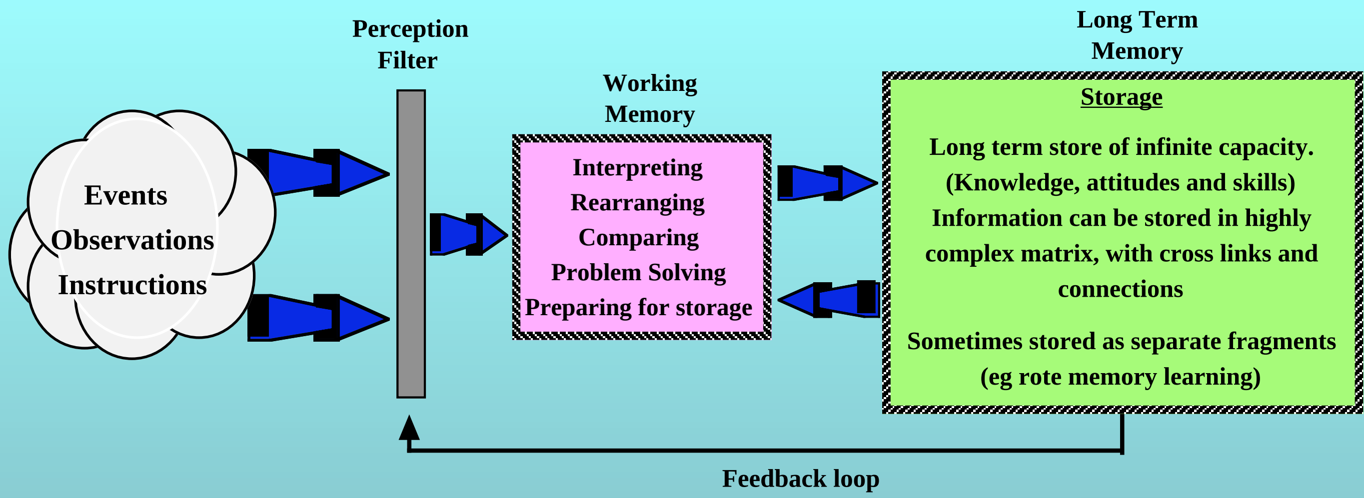
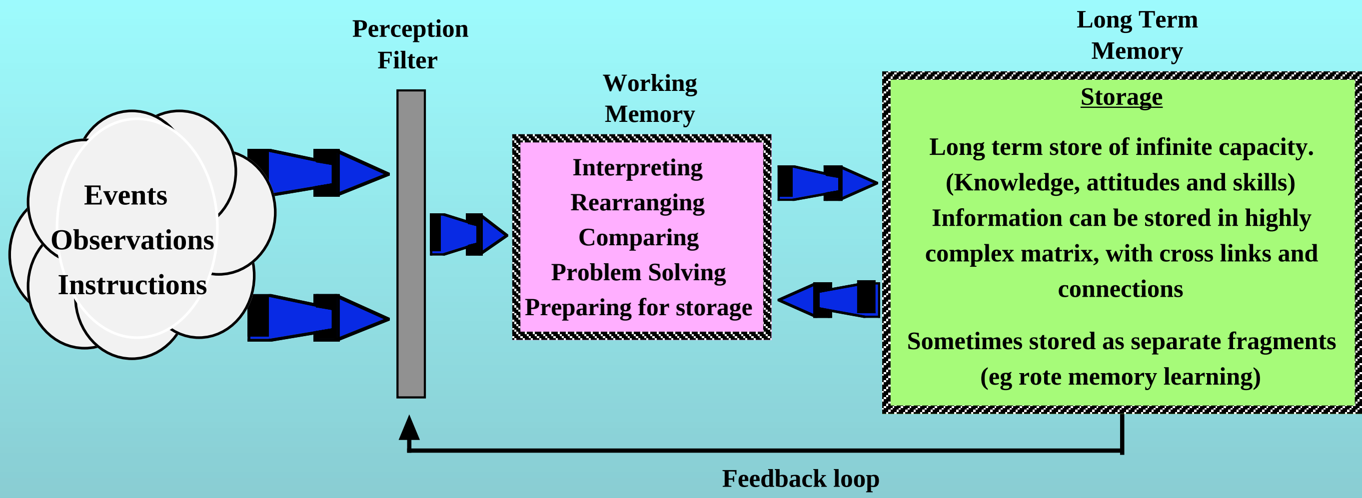


Pre-learning

- Improve Selection

Re-design presentation

- Lower Working Memory demand
- Encourage Understanding



- Improve Selection
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- Encourage Understanding

Pre-learning

Re-design presentation

Emphasise links and assess for understanding

Teaching and Learning Successfully in Physical Sciences

Stimulating and Enjoyable ?

Teaching and Learning Successfully in Physical Sciences

Stimulating and Enjoyable ?

What does Research Evidence tell us about attitudes ?

How to Attract Learners to Physical Sciences

How to Attract Learners to Physical Sciences

Some Key Research Findings

How to Attract Learners to Physical Sciences

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- Interest develops early (by age 14)

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- Interest develops early (by age 14)
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- School teachers have a very critical role
- Things outside the school have almost no impact
- There is a successful curriculum approach
- Integrated science courses are disasters
- Career potential must be perceived

A Successful Curriculum Approach

A Successful Curriculum Approach

The Applications-Led Idea

A Successful Curriculum Approach

The Applications-Led Idea

My first encounter:

The findings of Elena Skryabina
in relation to Physics

What She Found

(greatly over-simplified)

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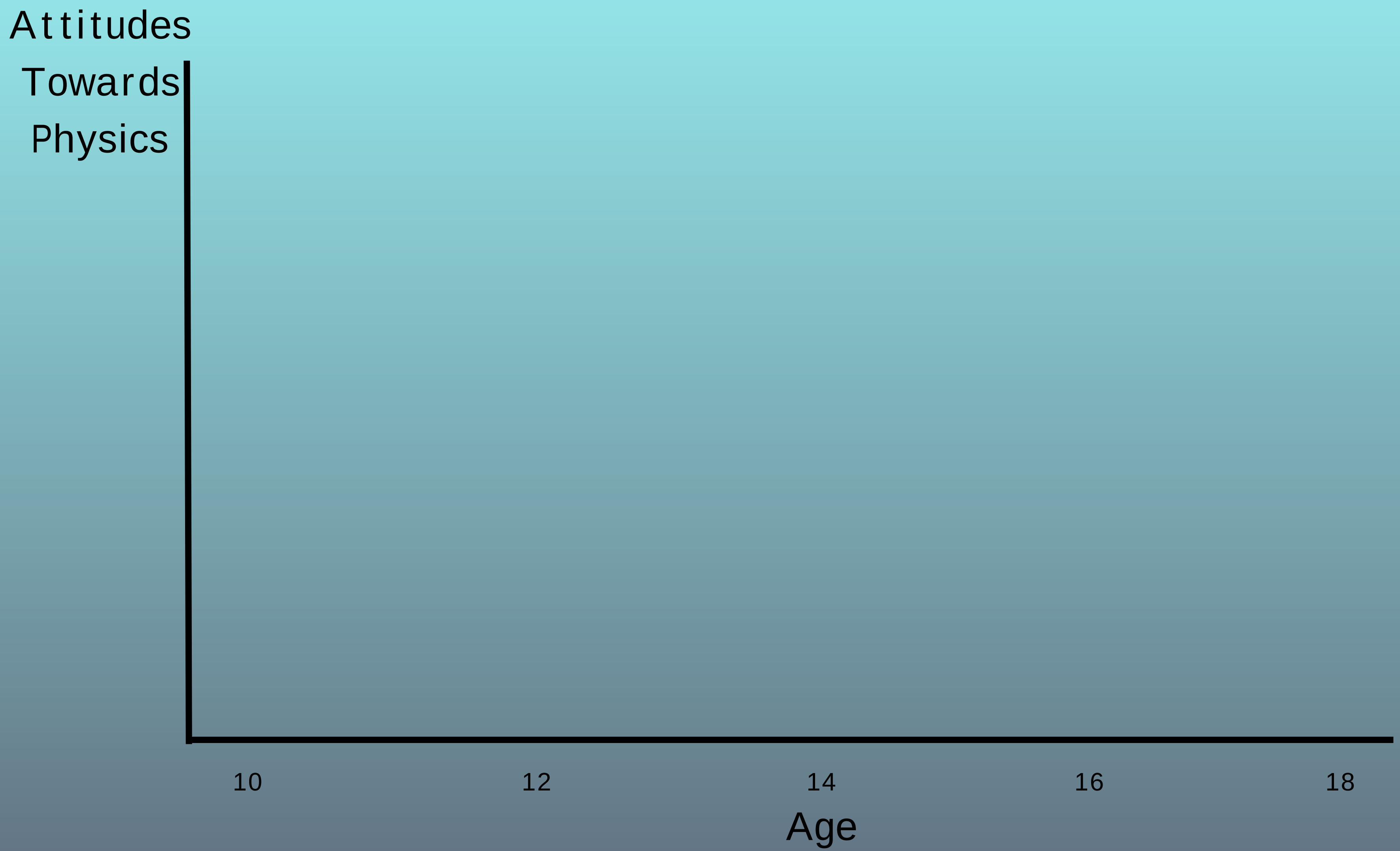

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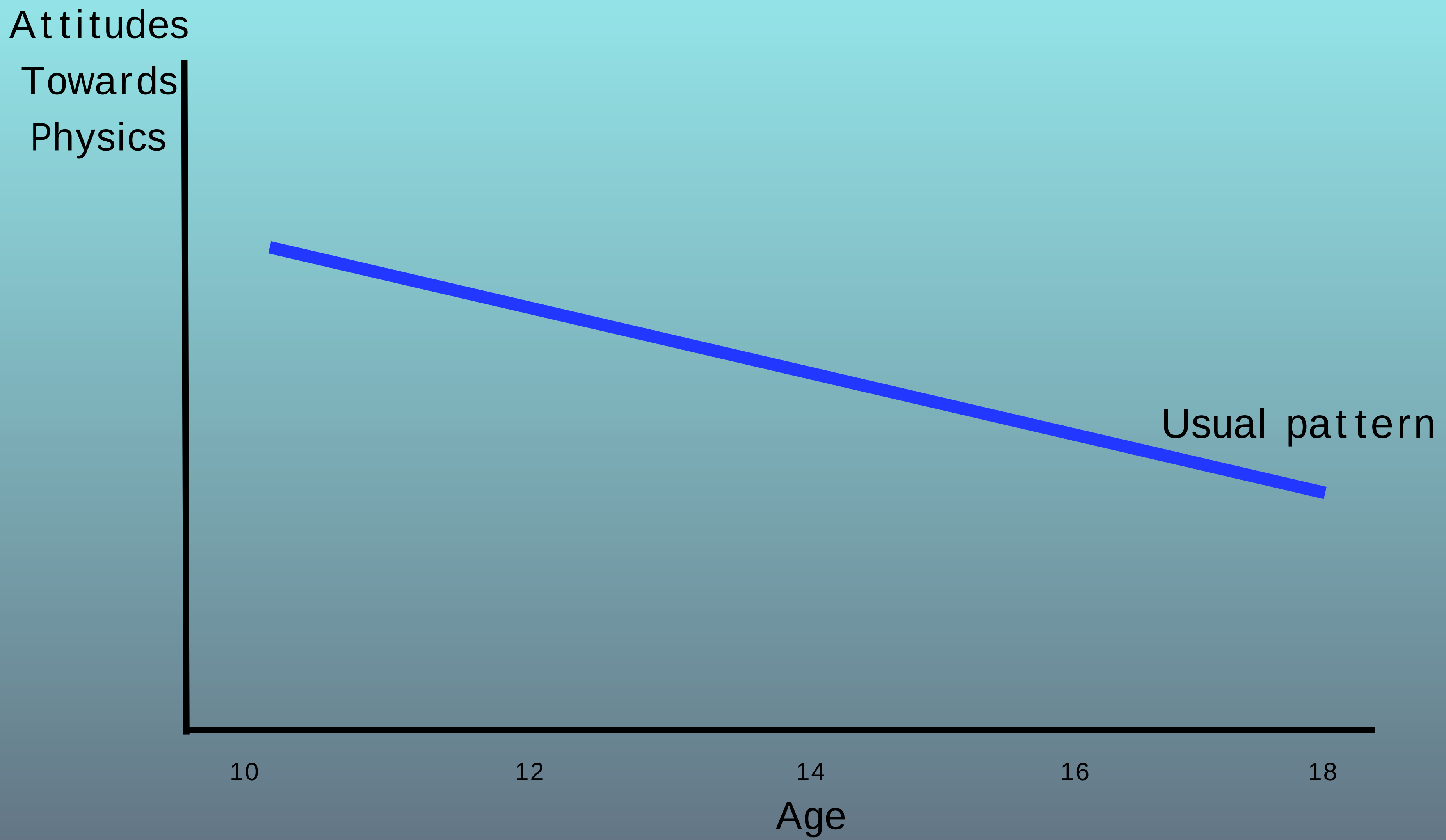
What She Found

(greatly over-simplified)



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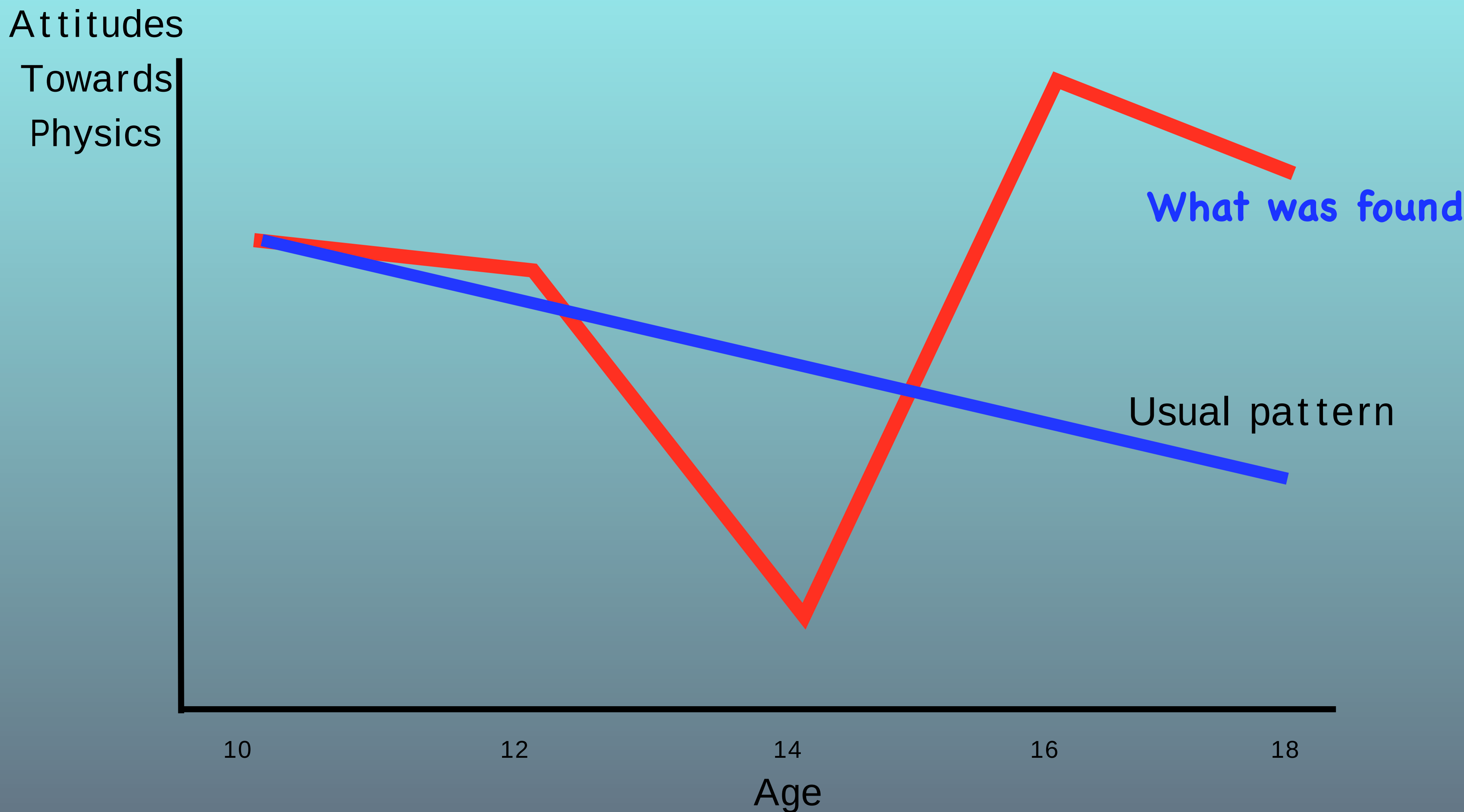

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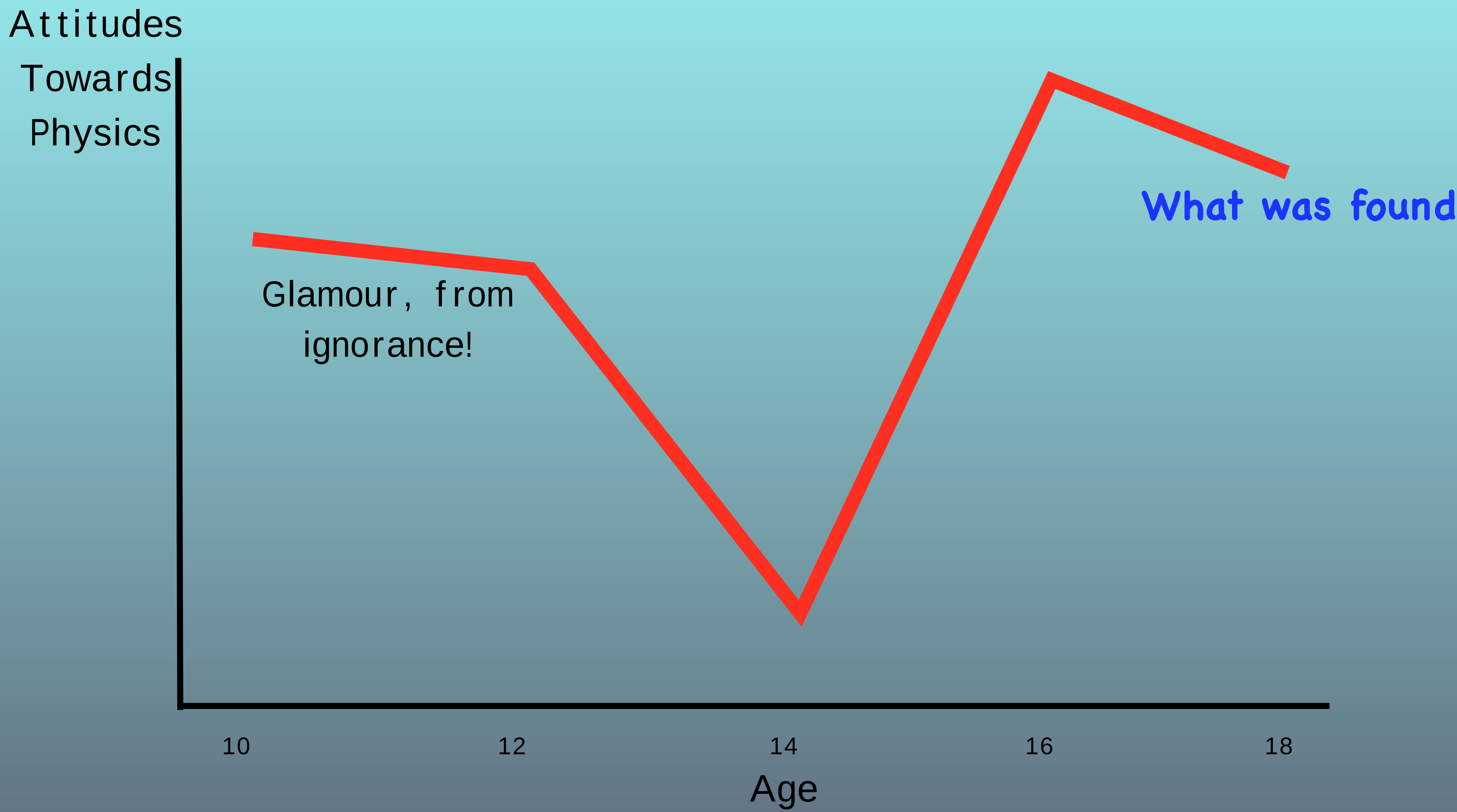

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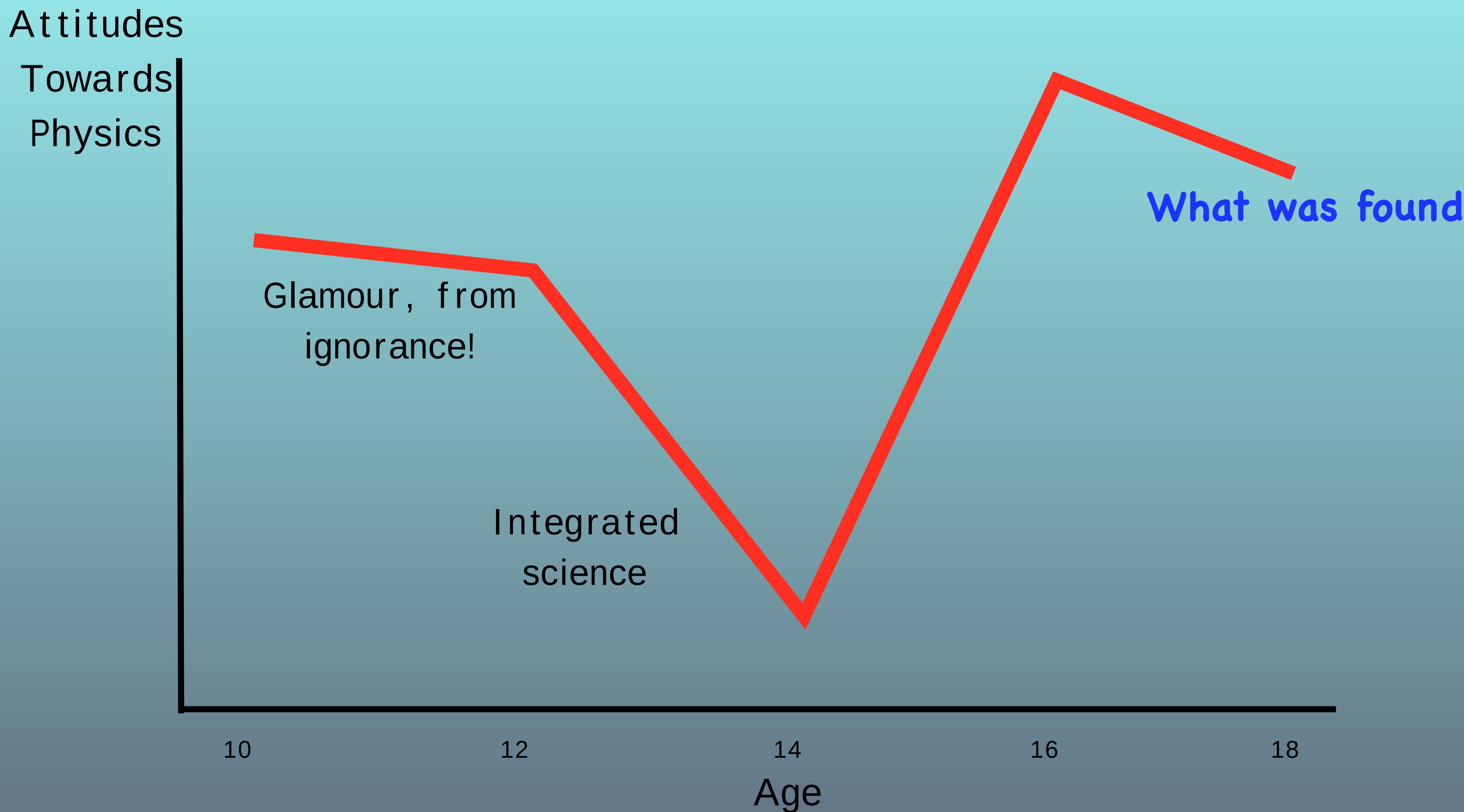

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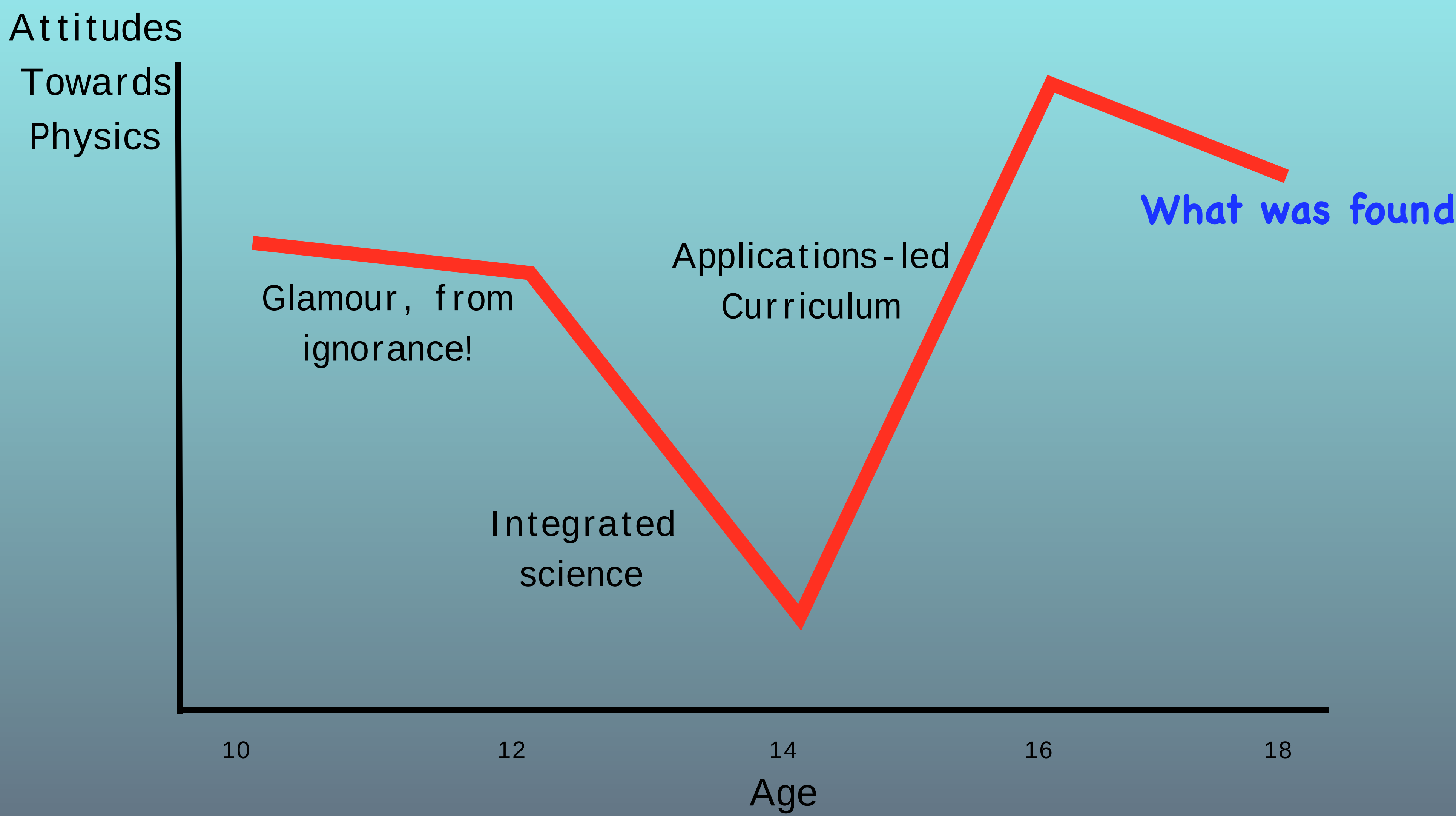

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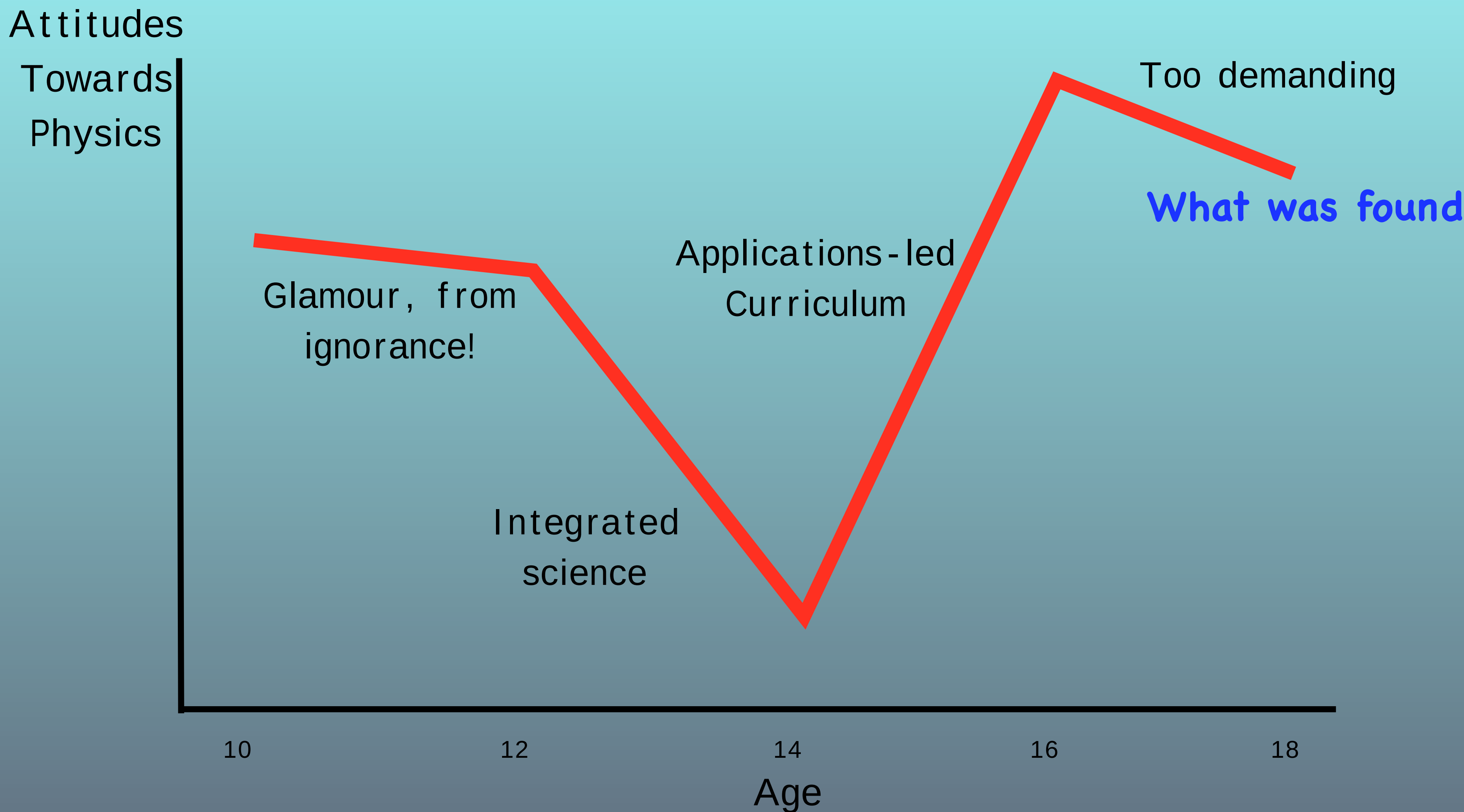

The Applications-led Syllabus

(Scotland aged 14-16)

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(Scotland aged 14-16)

1990

Unit 1: Telecommunication

Unit 2: Using Electricity

Unit 3: Health Physics

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The Applications-led Syllabus

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The Applications-led Syllabus

Possible Definition

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Towards an Application-Led Curriculum, Staff and Educational Development International, 1999, 3(1), 71-84.

More on Attitudes

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Positive Attitudes arise when:

- The curriculum is designed as applications-led
- It is taught by enthusiastic and supportive subject specialists

More on Attitudes

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What about the Working Memory Problem ??

Attitudes and Working Memory Capacity

Attitudes and Working Memory Capacity

Sample = 714, Aged 12-15 South Korea	Kendall's Tau-b Correlation
I am enjoying studying science	0.17
Science is interesting	0.13
Sciences is an important subject for my life	0.16

Attitudes and Working Memory Capacity

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The work of Eun Sook Jung in South Korea

Working Memory and Attitudes (2009) Research in Science and Technological Education

Attitudes and Working Memory Capacity

Attitudes and Working Memory Capacity

Are you interested in science?	Level 1			Level 3		
	High (N = 100)	Mid (N = 166)	Low (N = 98)	High (N = 95)	Mid (N = 172)	Low (N = 83)
YES	66%	55%	39%	48%	36%	22%
NO	33%	42%	57%	53%	64%	78%

Attitudes and Working Memory Capacity

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I have tried to understand science	71%	54%	50%	70%	61%	37%
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I have tried to understand science knowledge such as concepts, rules, theory as much as I can

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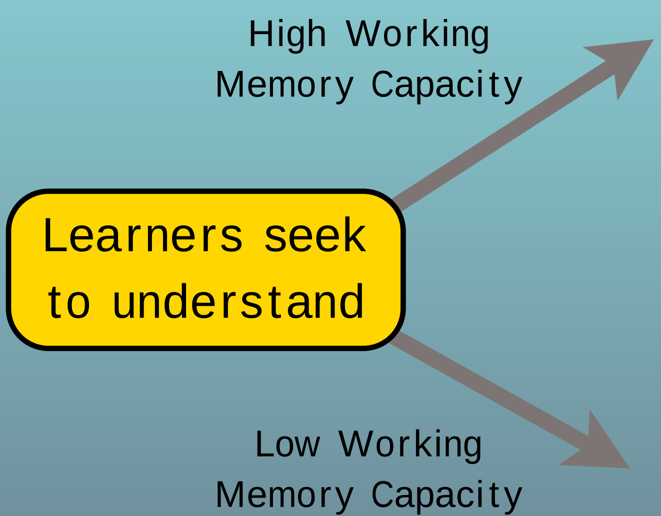
Attitudes and Working Memory Capacity

A Working Hypothesis

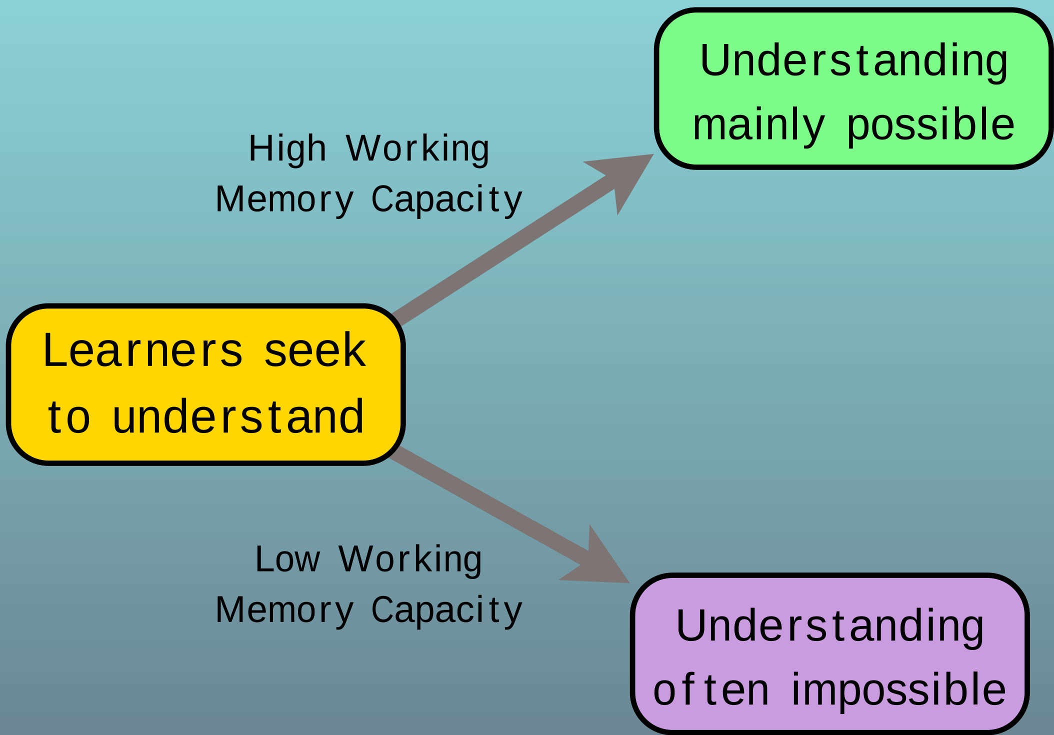
Attitudes and Working Memory Capacity

A Working Hypothesis



Attitudes and Working Memory Capacity

A Working Hypothesis



Attitudes and Working Memory Capacity

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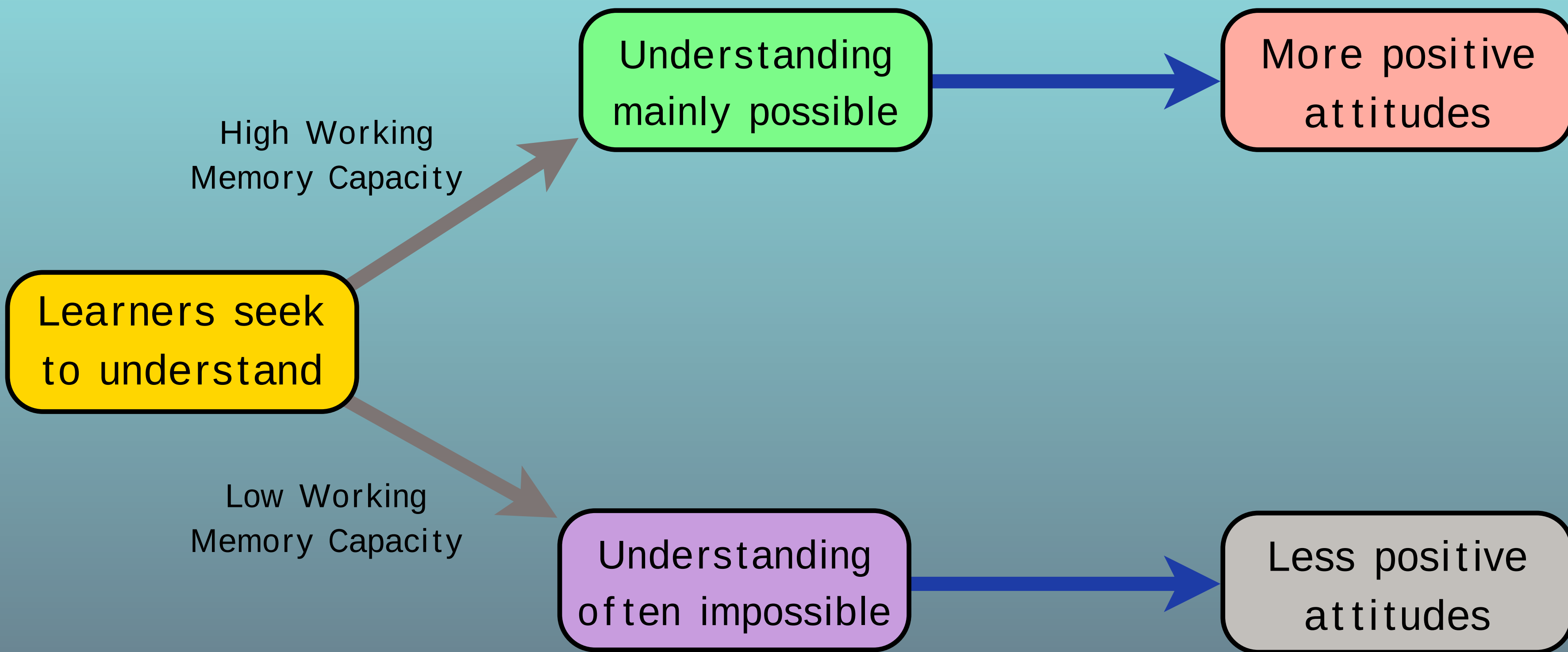

Making Learning Accessible, Stimulating and Enjoyable

What Does Research Tell Us ??

Accessible	
Stimulating	
Enjoyable	

Making Learning
Accessible, Stimulating and Enjoyable

What Does Research Tell Us ??

Accessible	Working Memory is Critical for Understanding
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Enjoyable	

Making Learning
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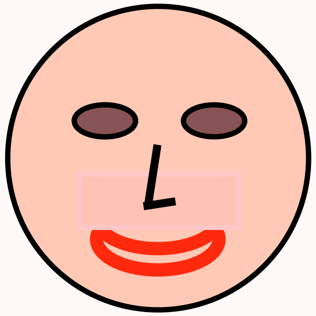
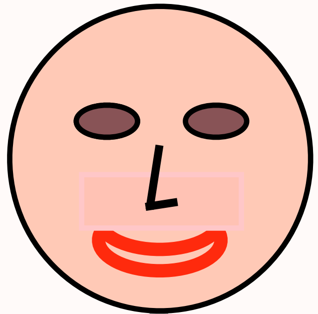
Enjoyable	

Making Learning Accessible, Stimulating and Enjoyable

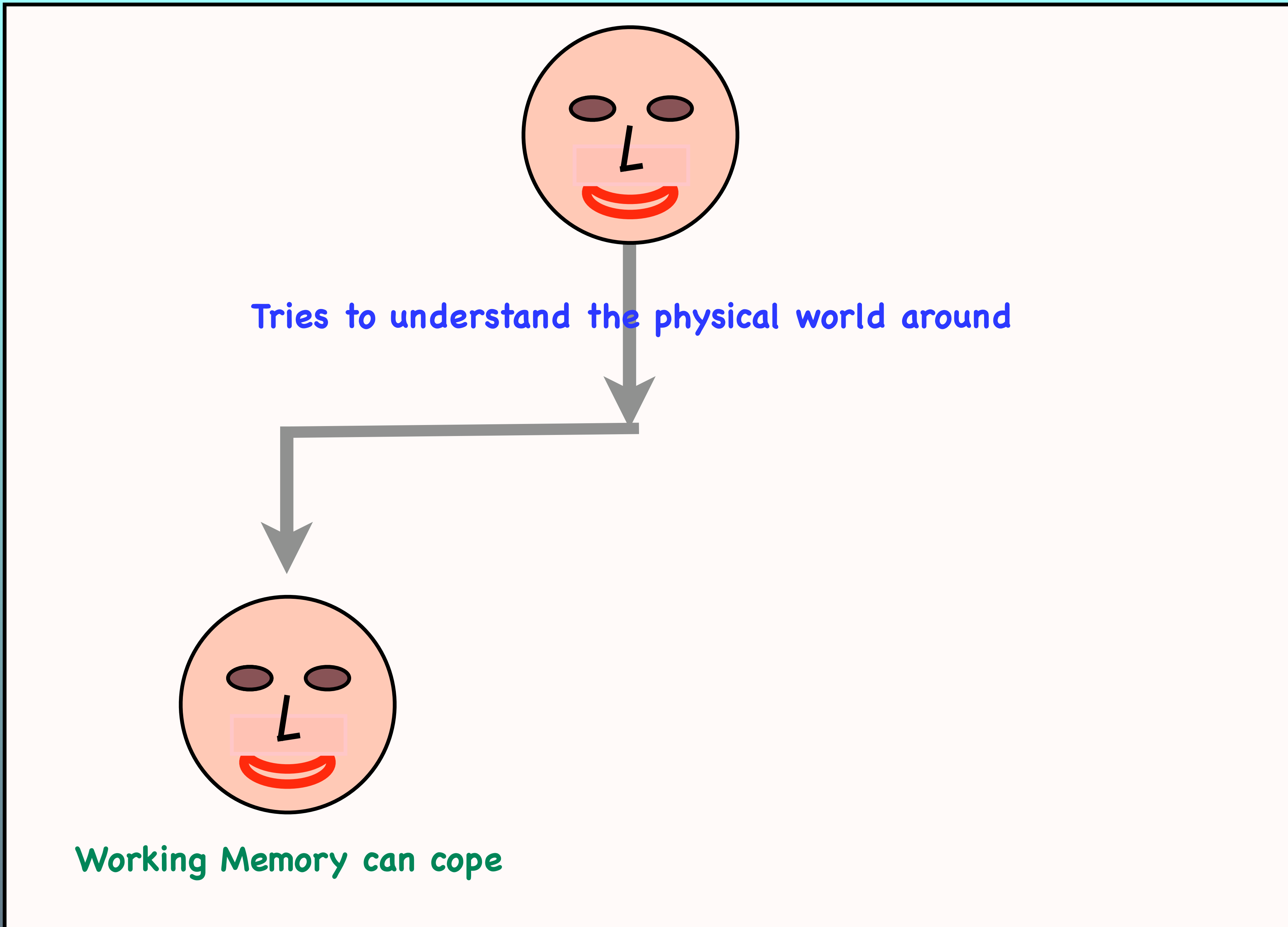
What Does Research Tell Us ??

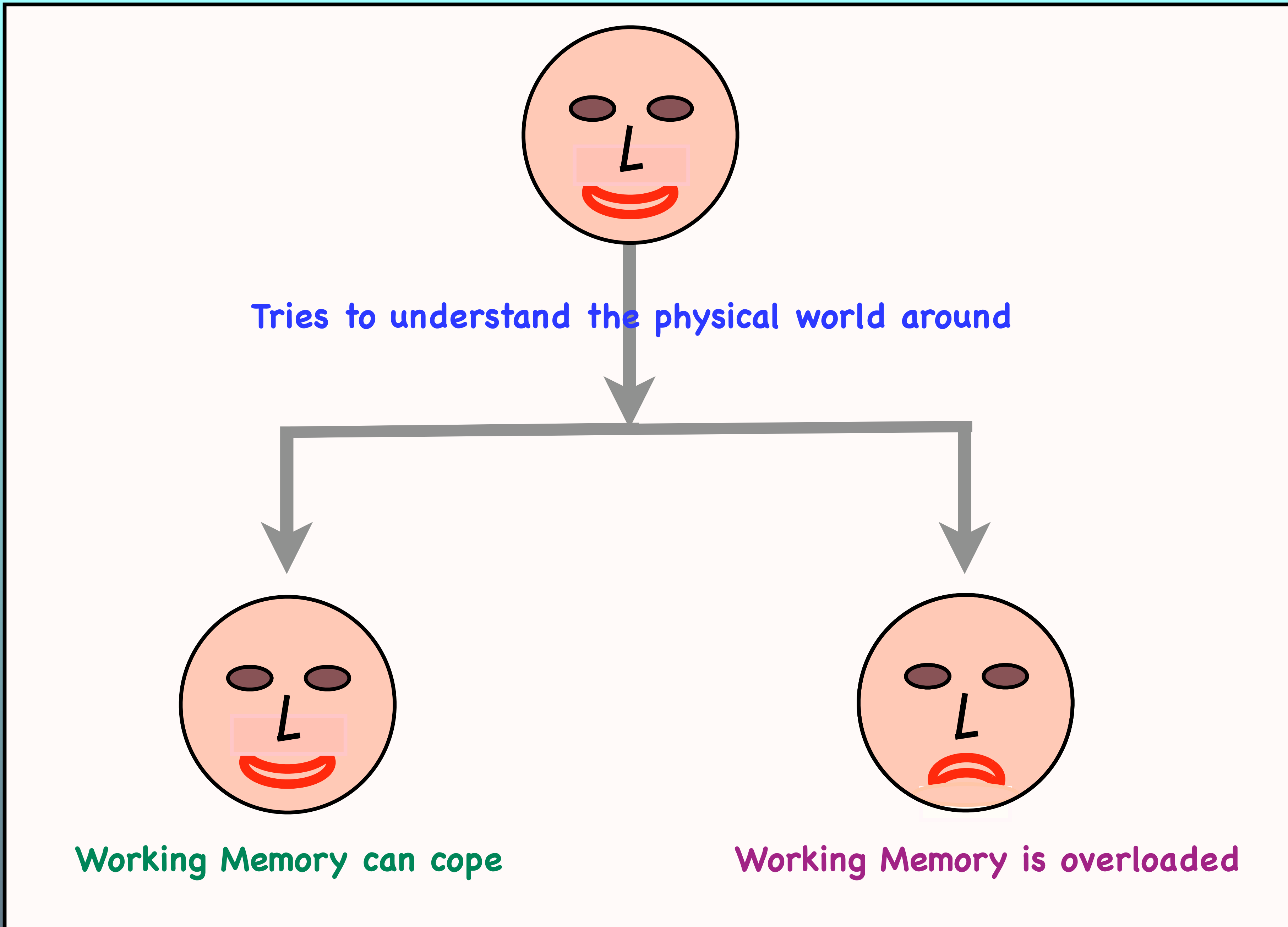
Accessible	Working Memory is Critical for Understanding
Stimulating	Presentation based on Meaningful Applications
Enjoyable	Understanding is critical for positive attitudes



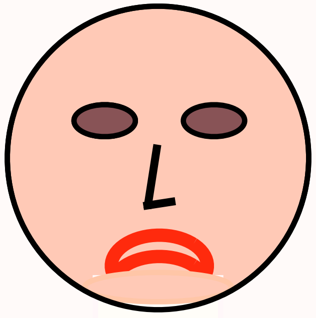


Tries to understand the physical world around


Tries to understand the physical world around
Working Memory can cope


Tries to understand the physical world around
Working Memory can cope
Working Memory is overloaded

I find it difficult

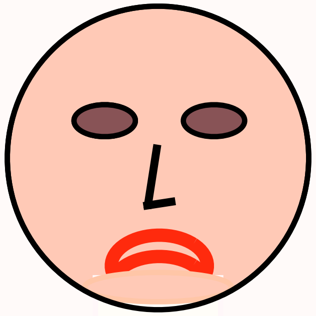


I cannot understand

I shall never understand

I shall give up and opt out

I find it difficult



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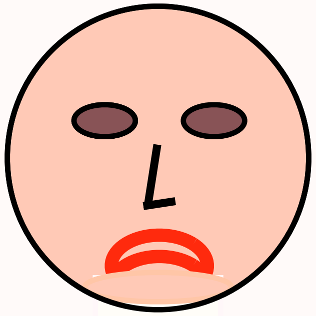
Working Memory is overloaded

Memorisation is the only way to pass

I find it difficult



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Working Memory is overloaded

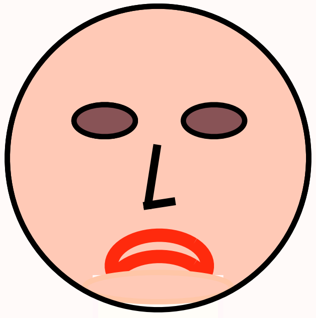
Memorisation is the only way to pass

I can cope

I can understand

I find it accessible, stimulating and enjoyable

I find it difficult



I cannot understand

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I shall give up and opt out

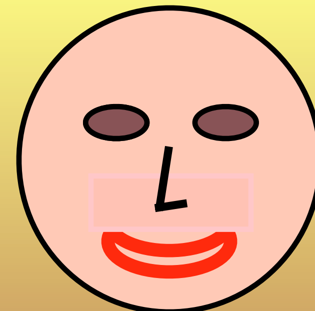
Working Memory
is overloaded

Memorisation is the
only way to pass

Working Memory
is coping

Understanding
is possible

I can cope



I can understand

I find it accessible,
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A Scientific Approach

to the

Teaching of Chemistry

Norman Reid

dr_n@btinternet.com

Centre for Science Education, University of Glasgow, Scotland

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Thank You

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