Thinking Like a Physicist about Physics Education

Work in progress.
Questions and discussion welcome and hoped for!

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A Few “Take-aways”

- **“Systems Thinking”** can help us understand HOW we learn through changes in the brain.

- Systems Thinking is needed in experimental physics research, especially in **simulations**, and leads to probability statements.

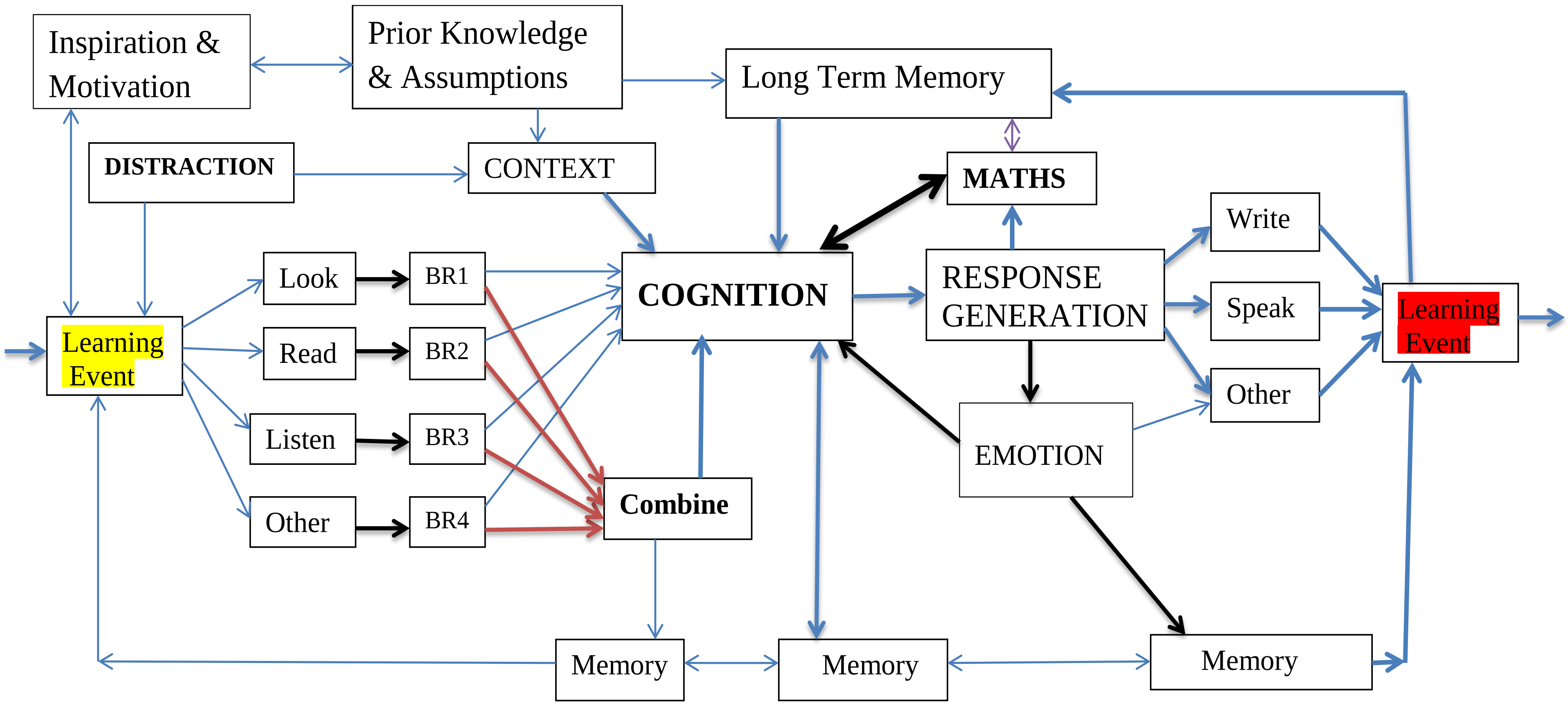
- Effective learning is greatly aided by 4 things
  - **MOTIVATION** based on prior interests and inspiration
  - An **EARLY glimpse of the mountain peaks** is inspirational
  - **EMOTION** and friendly interactions are important
  - Constructive and **early FEEDBACK is crucial**

Learning produces changes in the brain; HOW? What kind of changes? Can Systems Thinking help?

- **Systems Thinking** – a way of thinking about complex situations which clarifies causal links and is crucial for
  - Systems Analysis
  - Systems Engineering
  - Operations Research
  - SIMULATIONS (using Monte-Carlo methods)

- **Can we use Systems thinking to model learning?**
  - BIG PROBLEM!!! The human brain is very complex and modelling cognition is speculative.

- An **attempt to use systems thinking is on** next slide. Can we use it for simulations and calculation of probabilities to predict outcomes?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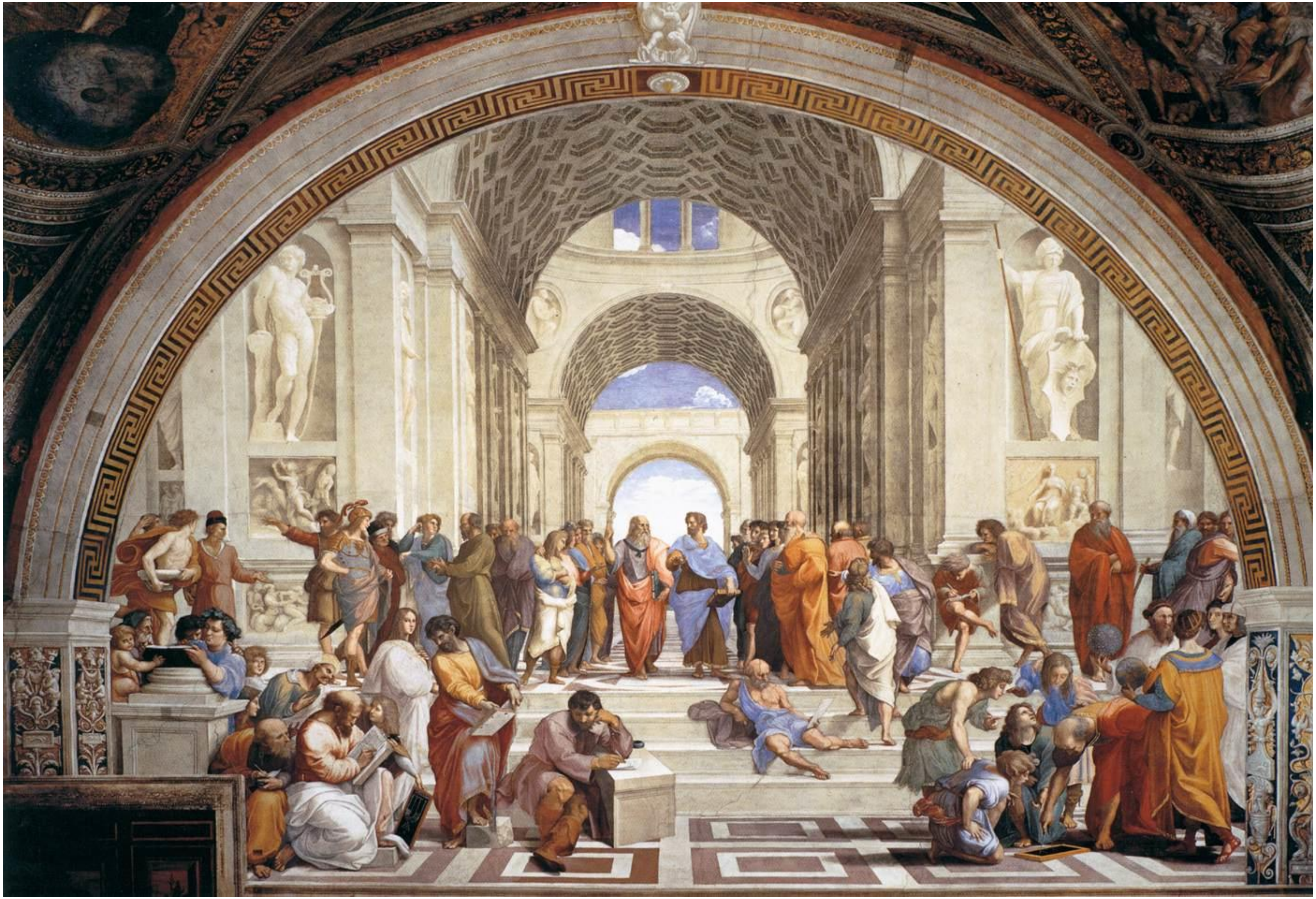
A few key quotes

- **“If we don’t know how we learn, how on Earth do we know how to teach?”**
  - *Rafael Reif, President of MIT (2017)*
- **“Education is the main accelerator of our brain”**
  - *How we Learn, Stanislas Dehaene, College de France (2020)*
- **“You should regard learning as a process of change.”**
  - *Study Success Booklet, Imperial College London (1990)*
- **“When all these studies reach the point of inter-communion and connection with one another … then will the pursuit of them have a value”**
  - *The Republic, Plato (380 BC)*

- ***Next Slide – Plato’s Academy, painting by Rafael: The first Institute of Higher Education. Note the similarity with the remodelled Lecture Theatre 2 !!!***



Raphael - The School of Athens (Copyright: the Vatican) 1511

Systems Thinking and Simulations

- **Systems Thinking and Systems Analysis**
  - Networks of components and processes of different types in which the topology of links and information flows are important, e.g. air defence systems, transport systems. **Results in PROBABILITY STATEMENTS!!**
  - Systems thinking led to **Operations Research** which was developed mainly by **Blackett in WWII** to combat U-boats. **It was the key to winning the Battle of the Atlantic.**

- **Simulation Computer programs in Particle Physics**
  - Detailed modelling of combinations of elementary processes in experiments using Monte-Carlo methods.
  - Vital for Experiment Design and analysis of results. Outputs are compared with real experimental results to help test physics theories.

Cognitive Neuroscience and Learning Physics

- Cognitive neuroscience is a vast and rapidly growing field of science which deals with the **extreme complexity** of networks of neurons (not only in *homo sapiens*)
- The main goals of most neuroscientists are to understand how brains function and how to treat neurological conditions. Few work on its application to the learning processes in education.
- Learning Physics is an interesting topic for neuroscience because “thinking like a physicist” starts at a very early age from a wish/need to understand the external world.

How does learning change the brain?

- **Practice** is the main brain change agent
- Neurons that control action fire repeatedly. If a neuron fires repeatedly it grows and extends out to other neurons. Signalling connections are called synapses
- **Networks of synapses are the physical equivalent of "knowledge" and "memory". They are dynamic.**
- Another agent for brain change is **EMOTION**.
- The more positively learners think about what they are learning and experiencing, the more likely they are to be engaged and happy and the better they learn.
- Conversely, stress, worry and boredom may compromise learning. So, **MAKE IT INTERESTING** and enjoyable.

Some Sources relevant to Cognitive processes in Learning

- Ordered sets of graphs of networks, dynamic cognitive maps and network control *(Ref: Danielle Bassett)*
- *Cognitive Processes in Learning (Stanislas Dehaine - especially his book "How we Learn – the New Science of Education and the Brain".*
- *Links to Machine Learning (Pedro Domingos - especially his book "The Master Algorithm")*
- *Artificial Intelligence (Alan Turing – especially his papers "Computing Machinery and Intelligence", 1950 and "Can Machines Think", 1954)*
- *Psychological Factors (Daniel Kahneman, "Thinking Fast and Slow")*
- *Very many Journals and books on cognitive neuroscience, computational neuroscience, cognitive psychology, …*
- *Caution! Some sources may be suspect e.g.* ***behaviorism*** *as a psychological underpinning to explain engagement and motivation via* ***rewards*** *(getting marks!) is like feeding pigeons and is now discredited.*

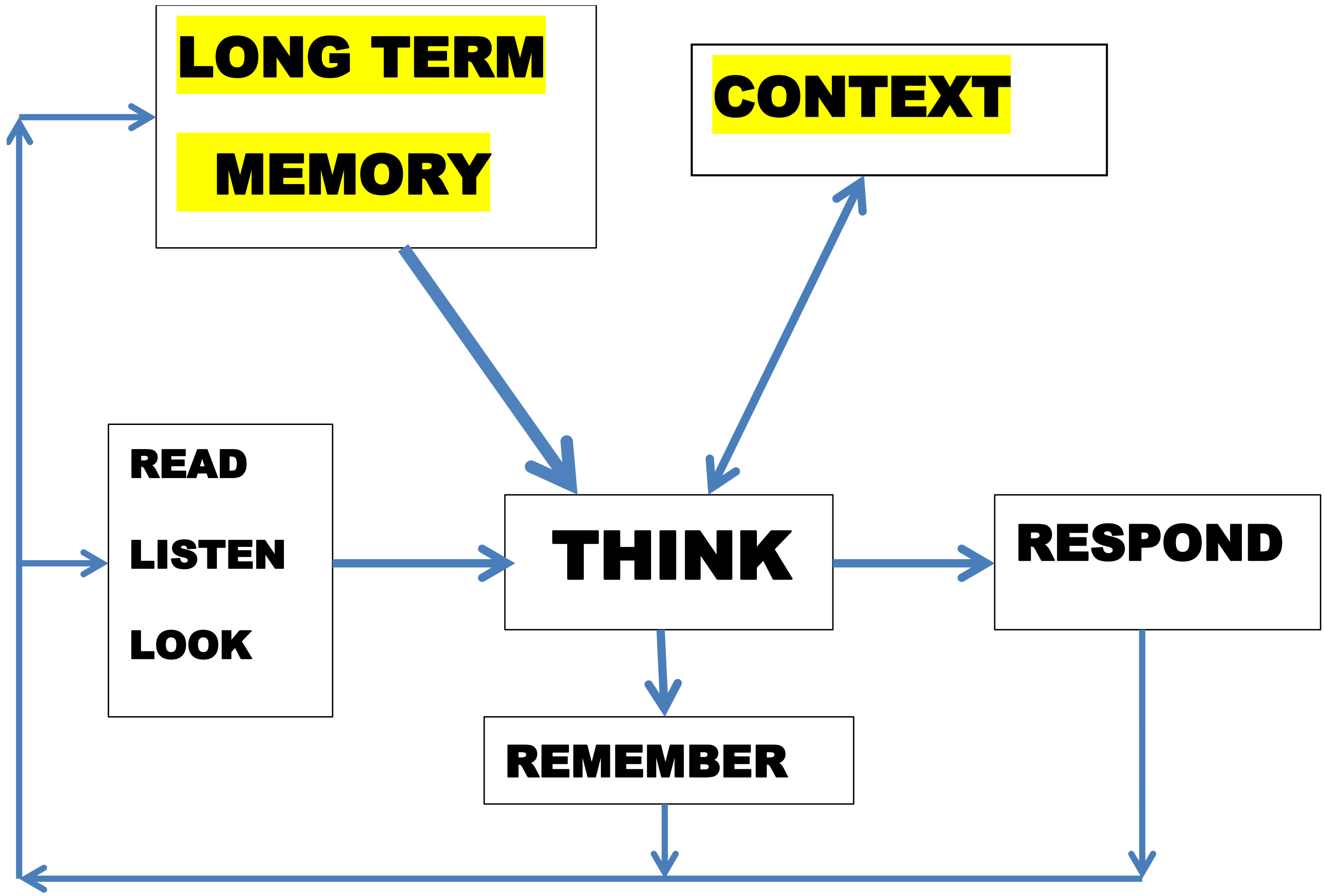
Neuroscience Research shows that there are 4 pillars to Learning (Dehaine)

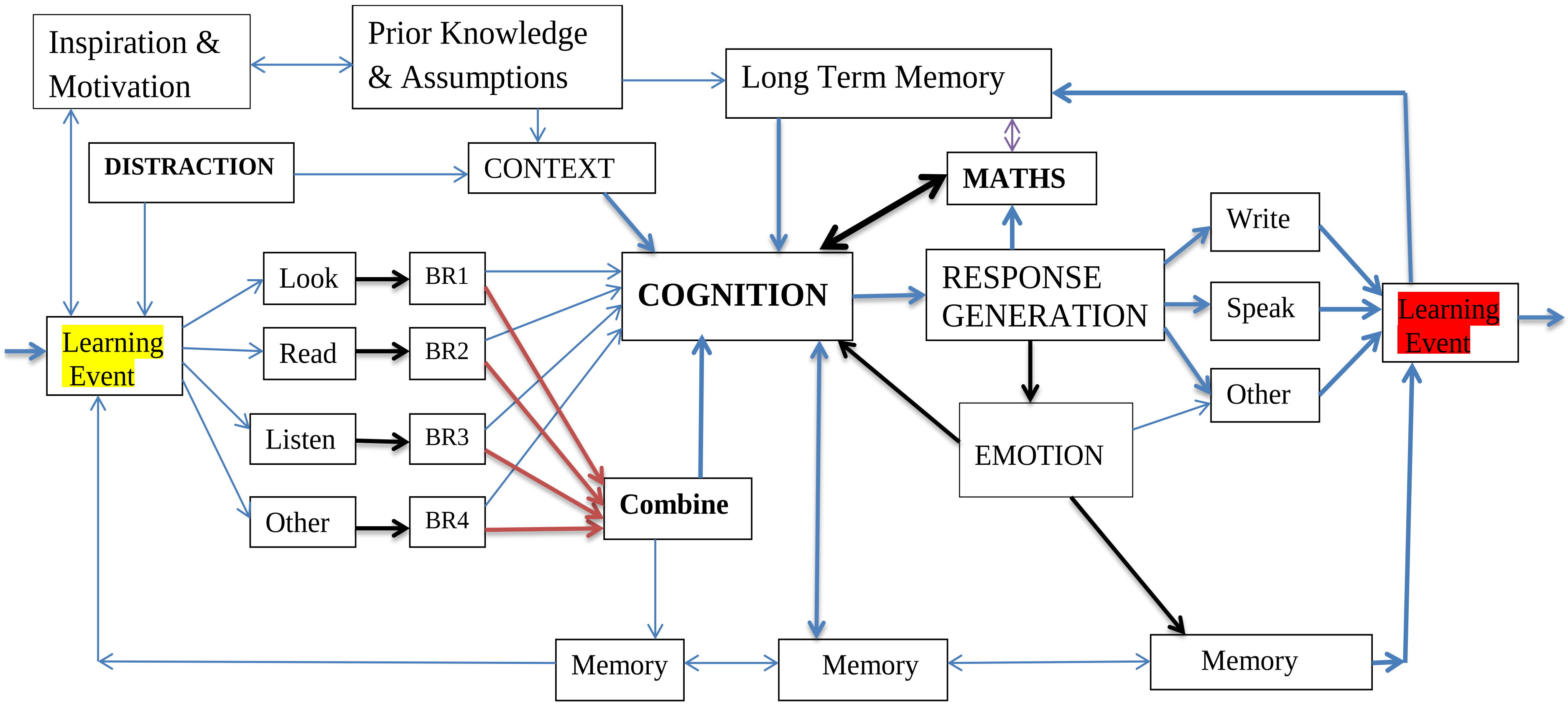
- Attention
  - Amplifies the information we focus on
- Active engagement
  - Curiosity motivation – a wish/need to "know and understand": an algorithm tests hypotheses by cognitive processes – model building.
- Feedback
  - Compares our beliefs/predictions with "reality" and corrects our models of the world
- Consolidation
  - Renders what we have learned automatically retrievable to be combined with new learning

Modelling the Learning Process

- **Motivation** leads to the intention of learning
- Start with information flows from the senses
  - Distinguish valuable inputs from distractions
- Combine information flows and compare with existing knowledge/models
- COGNITION
  - THINK about truth, meaning, relevance and connections with other models and previous knowledge
- **Respond** – ACT, USE, REMEMBER!
- Only model the system structures and links, don't attempt to model neuronal activity.

Studying to Learn

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Flow diagram showing links and loops

- A “Learning Event” usually starts on the left with sensory **inputs** (information flows) and **prior knowledge**/assumptions.
- Some of these are relevant and can be related to earlier inspiration and motivation. But they need to be distinguished from **distractions**.
- Pre-Processing of sensory information flows involving the eyes and ears is semi-automatic. This pre-processed information will be combined and then result in cognition but can also lead directly to cognition before being combined.
- Can add probability and other maths to diagram (a bit like a Feynman diagram).

Explanations of a few Boxes and Links

- **Learning Event**
  - Any interaction between a learner and a learning system
  - Can be active or passive but will contain internal loops
- **Inspiration which leads to Motivation**
- **Read**
  - Processing of coded visual information to generate thought
- **BR1, BR2, BR3, BR4, Combine (signals from senses are combined in a pre-cognition process)**
- **Distraction**
- **Prior Knowledge and Assumptions**
- **COGNITION**
- **RESPONSE GENERATION**
- **MATHS**
- **EMOTION**

Initial Processing of sensory data flows

- Basic sensory inputs relevant to learning are mainly produced by the eyes and ears.
- Pre-processing of these sensory inputs lead to **reading and listening but also extracting meaning from diagrams and pictures.** Both involve **pattern recognition and decoding** (preceded by semi-automatic pre-processing including combining signals) followed by interpretation and making links which are cognitive processes.
- Obvious examples of teaching methods involving both eyes and ears simultaneously are lectures and tutorials.
- **B**asic **O**ptically **O**riented **K**nowledge **S**ystems (BOOKS) were a big advance in learning methods as well as knowledge storage.
- Combinations with both **physical** and **mental activity** improves learning efficacy (ACTIVE LEARNING) especially in ways which test comprehension – Practical work – doing experiments.

Inspiration and Motivation

- An **ESSENTIAL** pre-curser for effective learning
  - Many Educational Psychology investigations show this
- "Why am I doing this?" "Is it interesting?"
- Motivation will vary from student to student, but
  - There is strong evidence that the main motivation for wanting to study physics at university is a wish to understand (at a high level) the world around us and the universe as a whole. This starts at a very early age and is **linked to evolutionary factors**.
  - It is a progressive process – one question leads to another.
  - Some questions are very difficult to answer - **CHALLENGE**

MOTIVATION and Distraction

- In 1st Yr of Uni, motivation comes from intrinsic interest in topics (often particular topics).
- In physics this starts in childhood and is enhanced by **encouragement and success**
  - In 3rd and 4th Yr driven by career possibilities.
- **Distraction** is a blockage to concentration on the subject/content being studied/presented
  - Overloading of processing of sensory inputs
  - Competing thoughts imposed by others e.g. "Do you think Arsenal will win tonight?" or by oneself e.g. personal issues.

More on Motivation and Rewards

- Early success at understanding physical phenomena will lead to (a) satisfaction (a reward) and (b) the emergence in our minds of truly challenging questions which lead to new ways of thinking, so want to study them at university.
- Some examples are (a) a wish to understand the universe at a fundamental level, (b) what are things made of, how do they behave?, (c) particular aspects of the world around us e.g. climate change, optical phenomena, space travel, (d) a wish to be challenged by difficult concepts, e.g. quantum physics, relativity, cosmology, mathematics as a way of deduction and new ways of thinking about solving problems.
- Physics students also want to learn how to apply physics to (a) solve practical problems, (b) develop new technology, (c) get an interesting and well-paid job, (d) help to tackle big problems facing the world, and/or (e) become an entrepreneur.

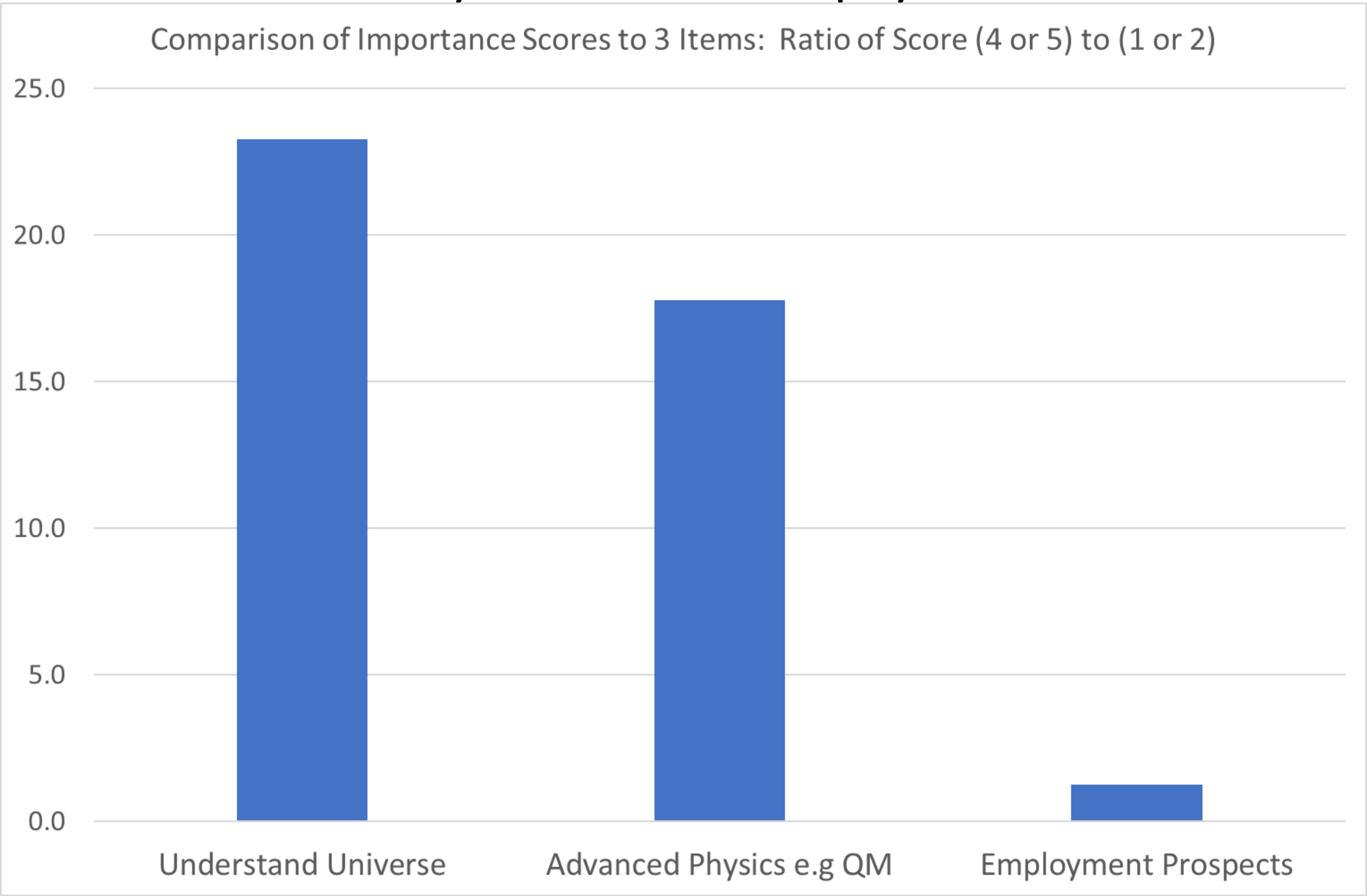
Some Evidence from a large Europe wide survey of 30,000 1st Yr Physics students

- 20+ questions on importance of a range of factors which contributed to decision to study physics at university.
- **Most important factors** were
  - **1. "Wish to acquire a deep understanding of the universe"**
  - **2. "A wish to understand the world around us"**
  - **3. "A wish to learn advanced physics (e.g. quantum mechanics) "**
- **Students gave an importance score, from 1 to 5, for each**
- **Distribution of importance scores for response : "Wish to acquire a deep understanding of the universe"**

Score	1	2	3	4	5
% of responses	2%	1%	10%	34%	53%

- **Remarkably similar results for all countries**

Why students chose physics



Important Implications for Curriculum Design

- Important to have some content in **1st Year** which relates to reasons why students chose to study physics
  - **A glimpse of the peaks** inspires you to climb “Mount Academic”.

- Recognise that **Maths is crucial** and is an interesting subject in its own right, **not just needed to do physics**, and has often been a key to major advances in physics.

- Do not overload with too much content – **inspire do not hammer** - **ENCOURAGE, do not punish**.

- Encourage **“Active Learning” in which the MIND is active**

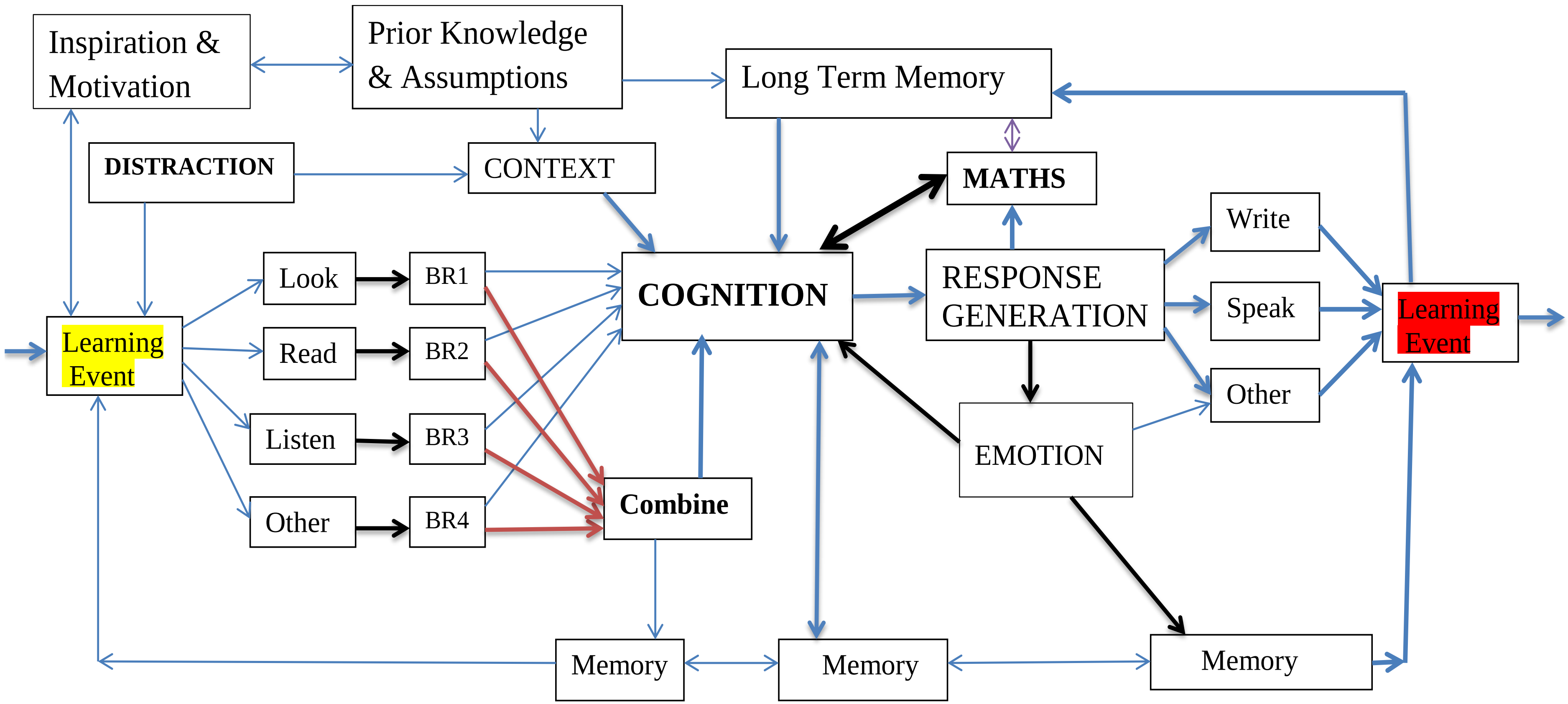
Some more General Boxes

- **Emotion**
  - Often overlooked but crucial for motivation and making progress.
  - "It was boring! It was interesting!" are feelings that have an effect on emotions and hence on progress in understanding.
  - the opportunity to engage with big questions is intrinsically satisfying – a challenge!

  - There is an important loop involving Cognition, Response and Emotion.   Emotion affects the next cognition!

  - Feynman: "The pleasure of finding things out", "It was fun".
  - Archimedes: "Eureka!"

  - Praise and Encouragement YES.   Discouragement NO.
  - Negative emotion is hidden and lack of self-confidence is SERIOUS.
  - Growing need for resilience to overcome negative emotion.



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EMOTION - linked to social interactions

- Praise and Encouragement YES – show empathy
- Discouragement NO. Leads to loss of self-confidence.

- Give feedback (promptly) as a prelude to advice on how to do better. Be aware that there are cultural sensitivities about what kind of feedback is wanted and how it is received.
- Even the opportunity to engage with big questions makes you happy. Progress in understanding makes you happy!
- Remember! Students have not only invested their money and time in studying with us but also they have INVESTED THEIR EMOTIONS. They hope and expect that they will not only work hard but that they will be happy. Happy that they decided to study physics, happy that they came here and happy socially.

EMOTION linked to
Explanations. Mysteries. New ways of thinking

- From a very early age we want to understand
- The eternal question "Why?".
  - "Please EXPLAIN". "Now I understand". When things are explained we are happier.
  - When something can NOT be explained (even by Feynman!), there is a different kind of happiness. New ideas or methods are stimulated which need creativity.
  - New ways of thinking may be needed which challenge accepted notions. These are intriguing and may lead to happiness.

Intense Emotion – a few personal examples

- Symmetry → Invariance → Conservation laws. Heisenberg's formulation of QM and Noether's Theorem.
- Mostly discovered in **Lectures** and by reading **Books.**
- Now I understand something which previously was a mystery. **A revelation!**
- Designing and making a detector and seeing it work.
- Seeing particle tracks with my own eyes, e.g. particle interactions in detectors.
- Such moments really make a difference and the incidents are remembered.

A few more Systems Features and Boxes

- **LOOPS**
  - Main mechanism for FEEDBACK and progression.
  - Difficulties faced by neuro-diverse students.
  - High functioning autistic students (twice exceptional)

    Good at accurate and fast cognitive loops (maths)

    but have difficulties with social interactions and speech
- **COGNITION**
  - The basis for "Active Learning" – the MIND must be active.
  - Links to memory are everywhere
  - Fast (jumping to conclusions?) or Slow (thinking carefully)
  - Speed and accuracy of thinking → academic success
  - The **brain is a product of evolution**.
  - Beware of Confirmatory Bias. Revolutions in thought take time.

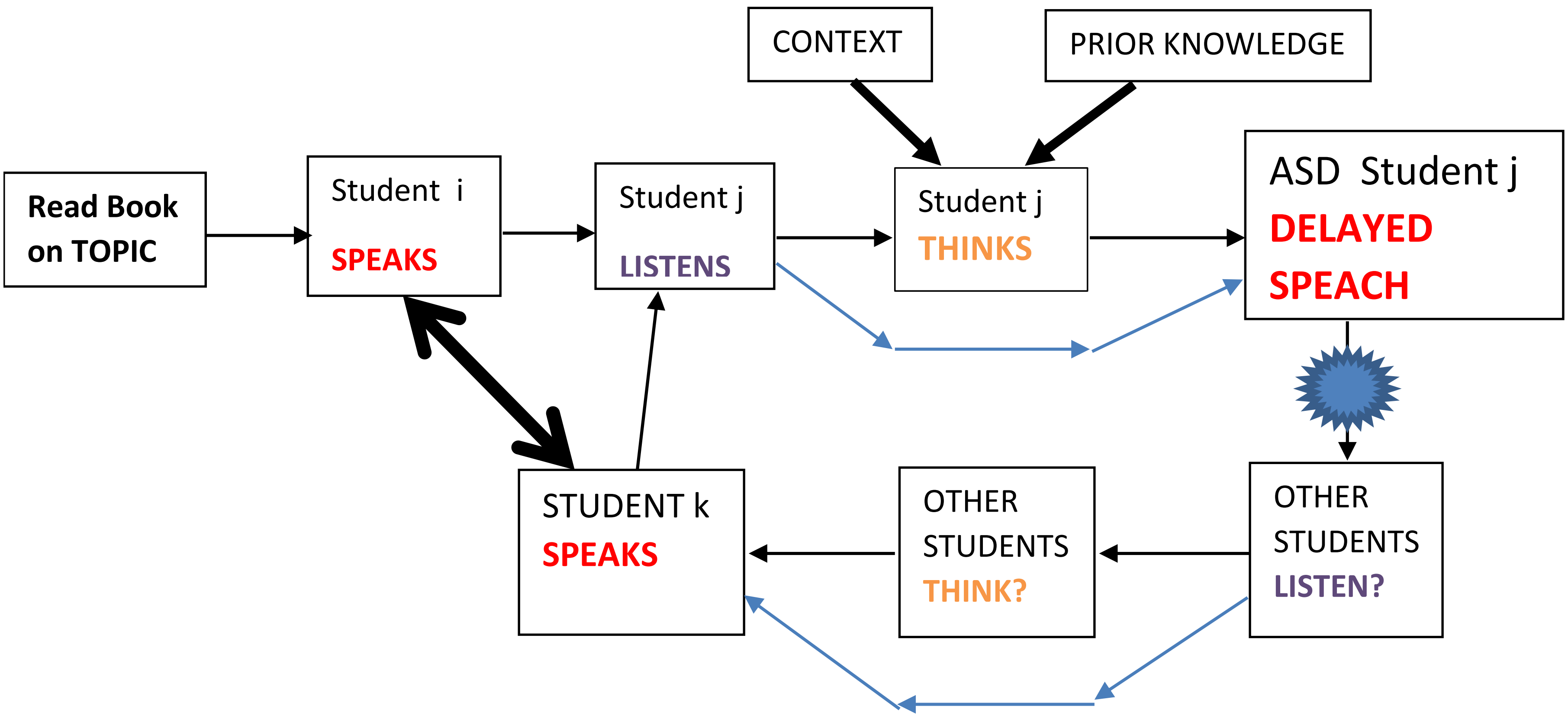
Maths Loop (multi-layered)

- In most of physics study processes, the use of mathematics is <u>VITAL</u> for effective cognition.
- <u>**Proven**</u> methods for investigating how A+B+C leads to X+Y+Z (and vice-versa) are crucial.
- It ensures that thinking is logically correct and that **correct conclusions are drawn**.
- It is a means of exploring the consequences of ideas and the links between experiments and theories.

Feedback and Error Correction

- **“Threat → Response”** errors have always had serious consequences. Error Correction ability was deeply seated in brains millions of years ago and feeds evolution. Those who do not correct such errors have a lower probability of surviving.
- But cognitive errors are **not easy to correct**. The reason can be found in the way our brain processes information and **creates templates** that we refer to again and again. These templates are essentially shortcuts, which help us make decisions in the real world. But these shortcuts, known as **heuristics**, can also make us repeat our errors. This is related to “Thinking fast and slow”.
- Error correction is one aspect of the crucial importance of feedback (from teacher to student and vice-versa) in education. There is a big advantage in this **feedback being given <u>sensitively</u> and <u>promptly</u>.**

Learning by Student Discussion Group when one student has Autism Spectrum Condition



Uses and Applications

- Aid to investigation and analysis of effectiveness of all forms of teaching and learning. **Programme design and ordering of topics.**
- Can recognise links and loops which can cause problems.
- Can adapt to make allowance for neuro-diverse students.
- Can make clear special features of some aspects of physics which require variations in learning processes.
- Helps to clarify special cognitive difficulties associated with paradigm shifts which require the rejection of models which seemed to be obviously true – question existing assumptions
- Has a clear use in developing, analysing and implementing teaching and learning methods, e.g. feedback and “active learning”.
- Is a starting point for simulation (mathematical and/or computer based) of learning processes which could lead to an “intelligent” student centred system.
- Link to ML or AI ??? Not by using AI constructs or LLMs but as a help in designing an **AI Educator**. **DANGER if in the hands of the wrong people!**

Active Learning

- Learning by doing has always been known to be effective.
- In some subjects there is a need for a lot of detailed learning of facts, followed by using them by established methods.
- But in physics, the learning of principles, fundamental "laws of nature", methods, ways of thinking, use of maths (particularly to make derivations and to explore consequences), ability to use devices, carry out and analyse experiments, problem solving techniques are far more important.
- In physics, active learning is particularly effective.
- One "old way" of active learning is to attend lectures, to **hand-write** notes (actively and cognitively, so engaging the mind) and **soon** after **revise/expand** on them and develop by using "**text books**", to **ask questions and discuss**, to follow up on particular topics, using them **to solve problems**, … New Ways should build on this.

COGNITION

- Cognitive ability is a consequence of the evolutionary processes involved in brain development over millions of years.
- Thinking fast and slow = jumping to conclusions or thinking carefully.
- Confirmatory bias: new ways of thinking about reality take time and repetition before being accepted.
- Error Correction feedback loops do not always work perfectly. The algorithm improves with use.
- Links to memory are everywhere.
- **Speed and accuracy of thinking lead to success**.
- It is only when **action** (doing something) involves **cognition** that it becomes a part of “Active Learning”.

Summary and Conclusions

- Physics Education involves changes in the brain of the learner (not in the arm!)
- What kinds of changes? – **NOT** just memory of facts, and acquiring skills. But also Cognitive changes (understanding).
- To cope with the extreme complexity of the brain, we can try developing a systems approach
- Loops involving: **MATHS, EMOTION, RESPONSE, FEEDBACK** are important.