Mechanisms for the Generation and Regulation of Sequential Behaviour

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The Issue

- A critical aspect of most human behaviour is the *sequential* generation of actions/responses/outputs
- Examples:
  - Language production
  - Routine action
  - Serial (and free) recall
  - PRP, task switching, and related RT tasks
- Key question:
  - How is sequential behaviour generated/regulated by the brain (cf. Lashley, 1951)?

Sequential Control and ACT-R

- ACT-R embodies a particular computational mechanism for sequencing behaviour
  - Production system control
- Alternative mechanisms exist:
  - Recurrent network; Turing machine, …
- Are there phenomena that may discriminate between sequential control mechanisms?
- If so, what challenges do they pose for ACT-R?

Subsidiary Questions / Strategy

- What computational mechanisms are capable of generating sequential behaviour?
- What kind of evidence might inform the debate?
  – That is, what evidence might discriminate between the possible mechanisms of sequential control?
- Does the evidence support/refute specific putative sequential control mechanisms?
- Aside: Similar debates within cognitive science:
  – local and/or distributed representations
  – single and/or dual route mechanisms

Plan / Overview

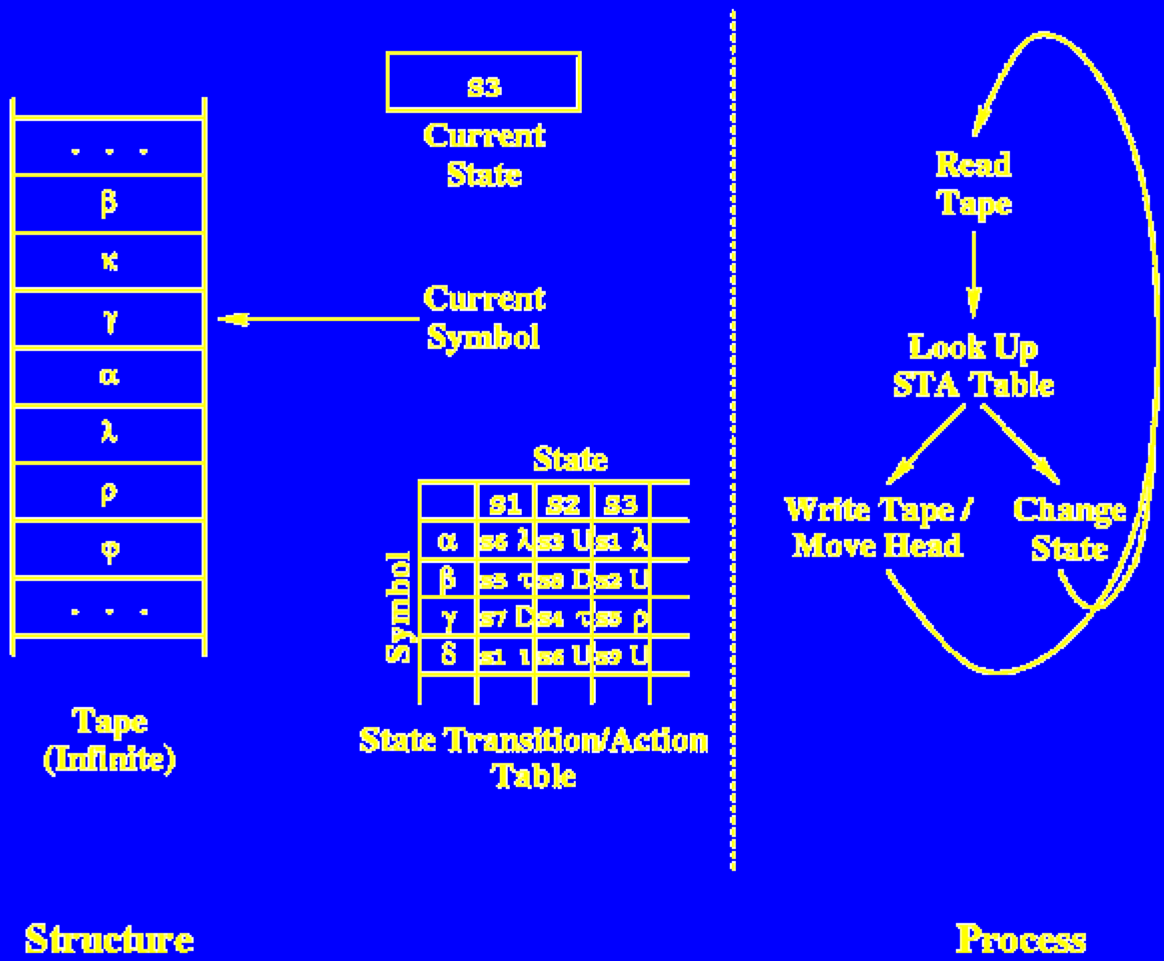
- A review of a variety of putative mechanisms
- Where does ACT-R fit in?
- Modularity: A subsidiary issue
- A catalogue of relevant effects
  - Overview of data
  - Relevance to control debate
  - Existing models and adequacy of control mechanisms
  - Issues for ACT-R
- Modularity revisited

Computational Mechanisms for Sequential Behaviour

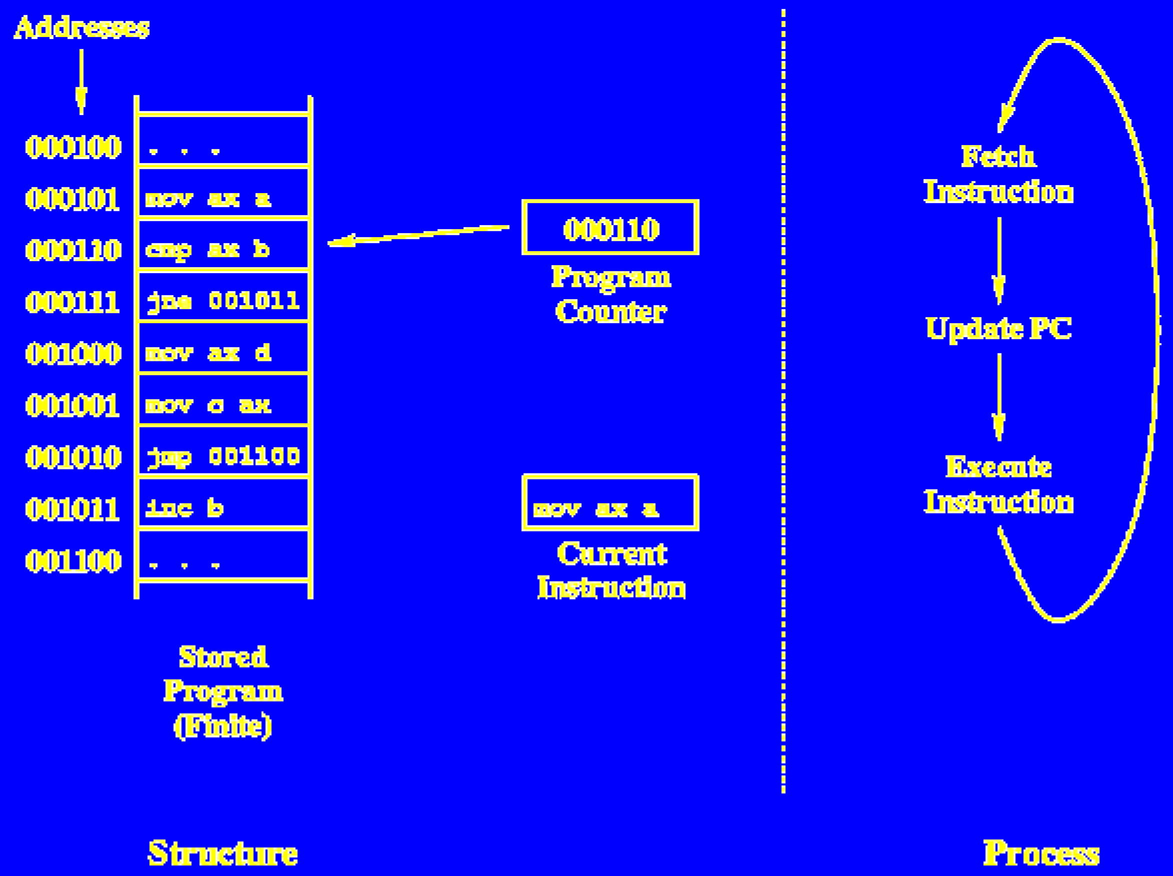
Several distinct computational mechanisms may support the generation and regulation of sequential behaviour:

1. Turing Machine (e.g., Wells, 1998)
2. Von Neumann Machine (e.g., Frawley, 1997, 2002)
3. Production System (e.g., Newell & Simon, 1972)
4. Operator Selection / Application Cycle (e.g., Newell, 1990)
5. Interactive Activation Network (e.g., Rumelhart & Norman, 1982)
6. Recurrent Network (e.g, Elman, 1990)
7. Others: the dynamical approach (Port & van Gelder, 1995)

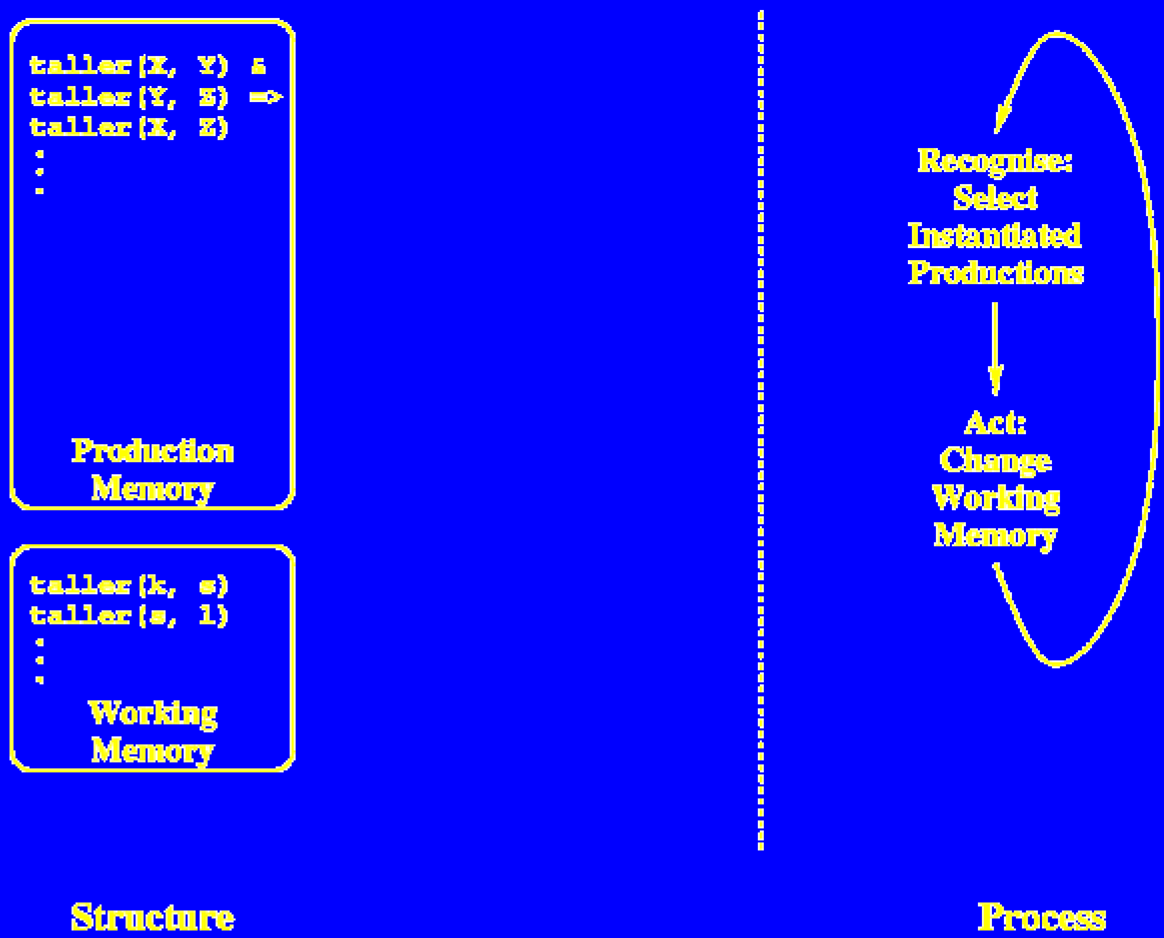
Turing Machines: Structure and Process



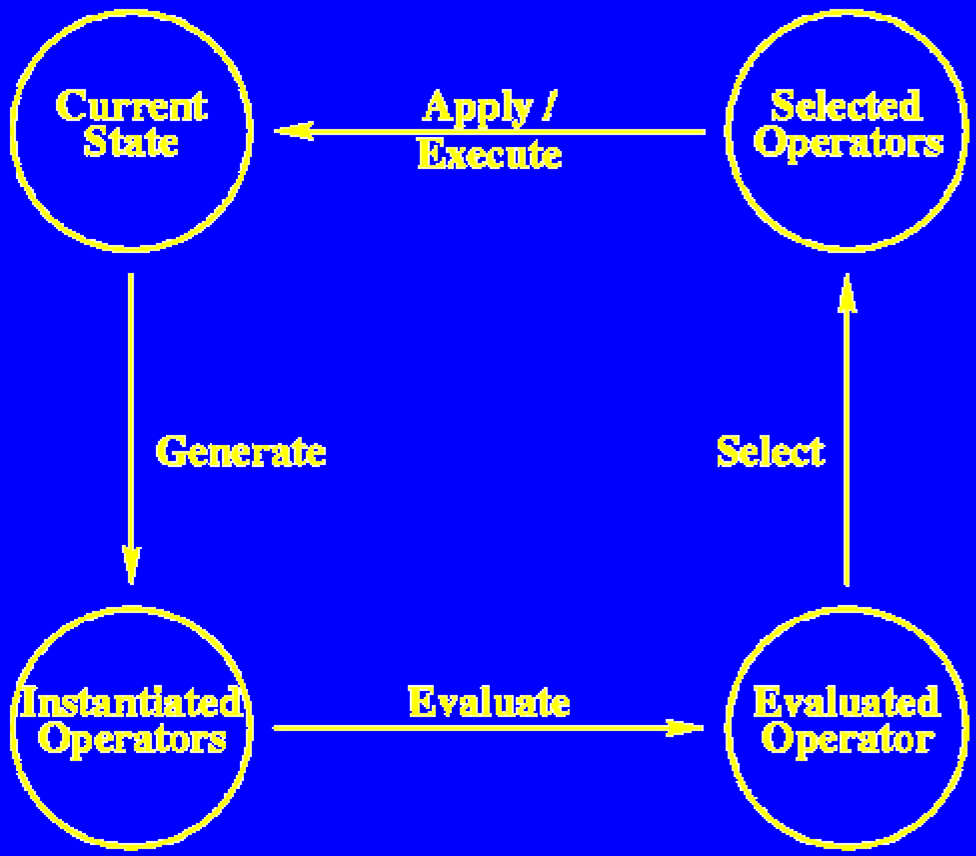
Von Neumann Machines: Structure and Process



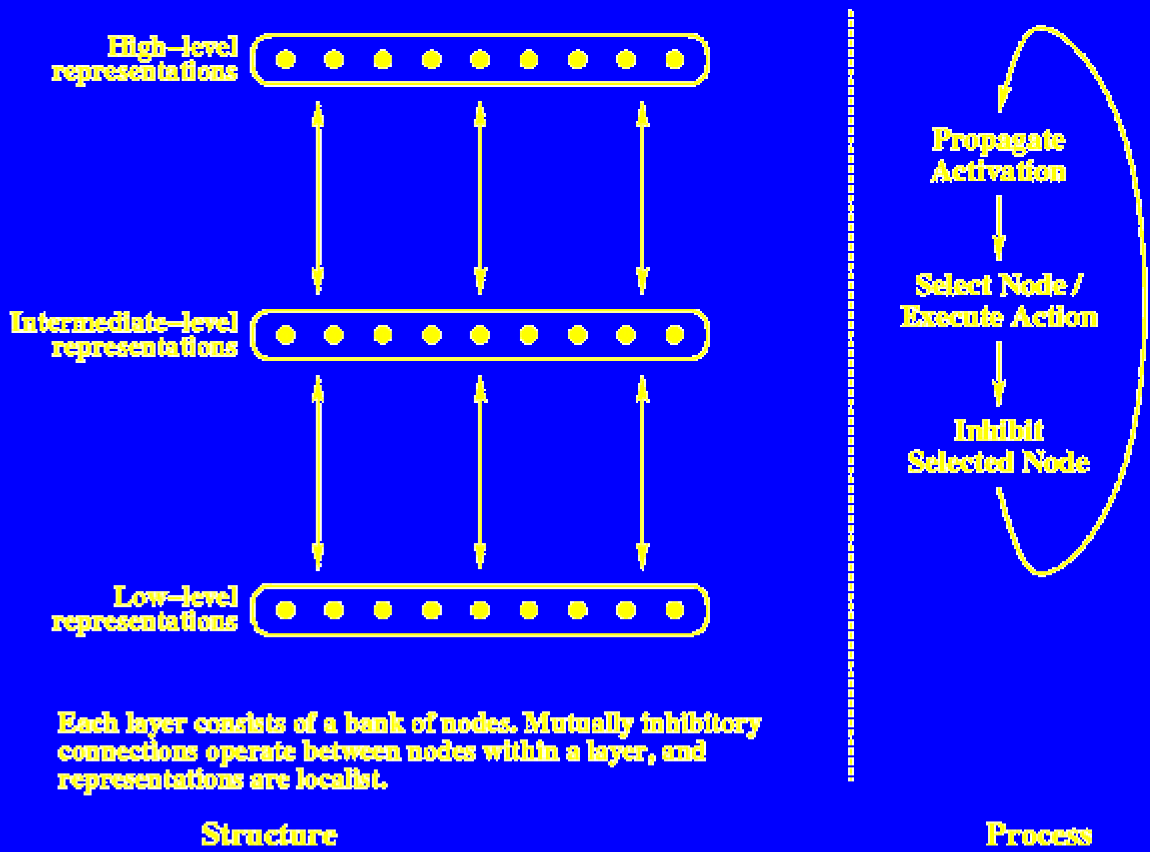
Production Systems: Structure and Process



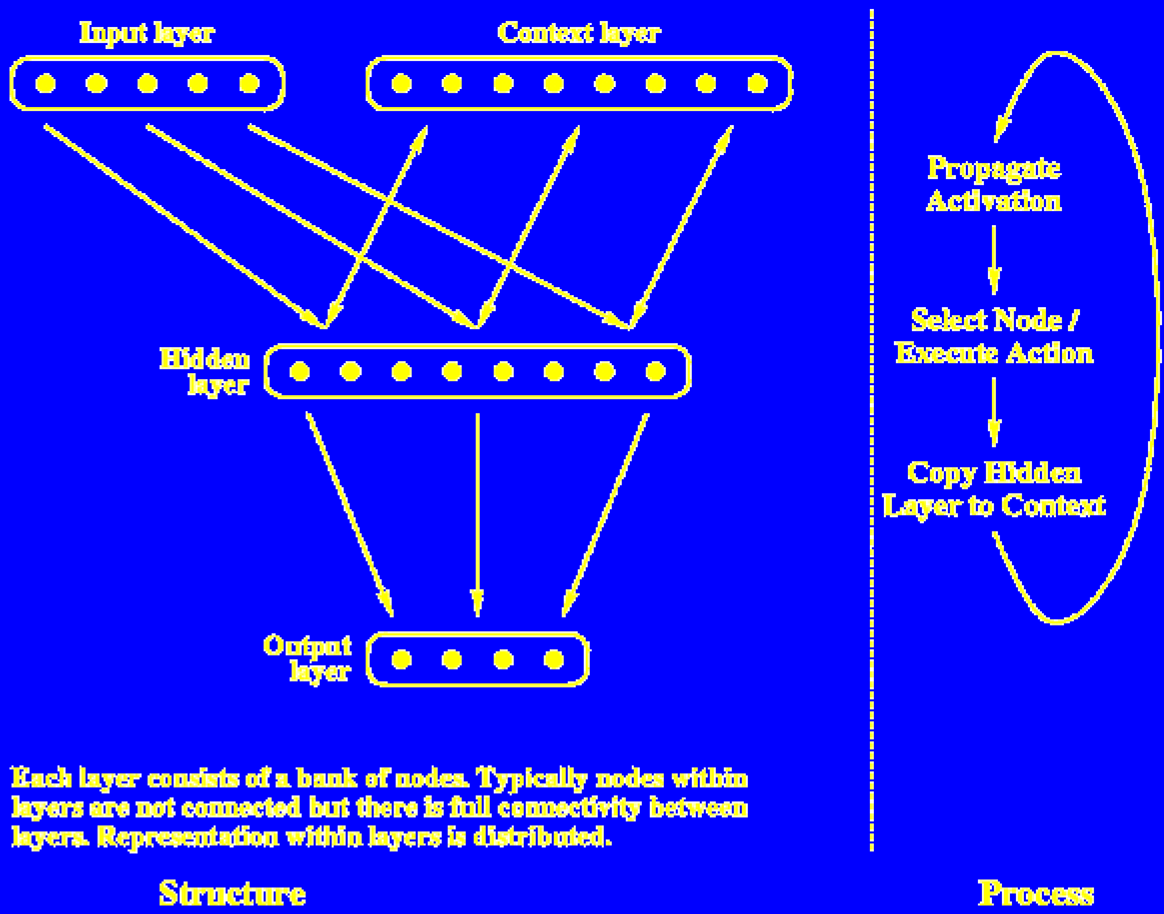
Operator Selection / Application: Process



Interactive Activation Networks: Structure and Process



Recurrent Networks: Structure and Process



Where Does ACT-R Fit In?

- Production system control with a twist:
  - Activation-based selection of production instances
  - The activation-based substrate is similar to interactive activation control, but …
  - there are no layers of representations, no inhibitory connections, no competition between units …
- An aside:
  - Unlike Soar, ACT-R does not dictate use of an operator selection/application control model
  - Instead, constraints on ACT-R productions come from the activation-based substrate

Two Straw Men

- Few (if any!) serious cognitive models make use of Turing machine or Von Neumann machine control

- They are straw men used by:
  - proponents of non-symbolic approaches who aim to discredit symbolic models of cognitive processes
  - non-computational/philosophical types who advocate symbolic models and respond to the bait

- They will not be considered further in this talk

A Subsidiary Issue: Modularity

- The Fodorian view (Fodor, 1983):
  - The cognitive architecture comprises a central processor interacting with the world via input/output processes
  - Input and output processes are modular:
    - Domain-specific, mandatory, fast, produce “shallow” outputs, informationally encapsulated, and cognitively impenetrable
  - Central processes are equipotential:
    - Domain-general, interruptible, slow, involve “rich” representations, informationally rich and cognitively penetrable

A Subsidiary Issue: Modularity

- ACT-R/PM maps well onto the Fodorian view, but…
  - Wells (1998) argues against modular I/O processes
  - Shallice (1988) argues against an equipotential central processor
  - (and the current version of ACT-R treats “central” processes such as retrieval as modular)
- Relevance to (sequential) behaviour:
  - Modular systems require structures or processes to coordinate modules

Modularity: Implications

- Modularity raises questions for each regime:
  - Can we design control mechanisms to support a modular Turing machine/production system/interactive activation network/recurrent network/…?
- If accepted, modularity …
  - requires the regimes to be modified to support it,
  - but does not allow any specific regime to be dismissed
- Further examination of the alternatives requires a more detailed analysis of the empirical phenomena

Some Phenomena to be Addressed (An Incomplete List)

- Routine (sequential) action
- Disorders of action
- Action monitoring and error recovery
- RT effects:
  - Robust between trial effects
  - PRP effects and switch costs
  - Negative priming and inhibition of return
- Handling interruptions and interleaving of tasks

Routine Action: Action Slips and Lapses

- Routine action is prone to numerous types of error (Reason, 1974; Norman, 1981):
  - Anticipation/omission errors
  - Substitution errors
  - Perseverative errors
  - Capture errors
  - Post-completion errors
  - …
- Errors are most frequent when fatigued or when attention is diverted (Reason, 1979)

Routine Action: Relevance to Sequential Control

- Claim:
  - The types of error to which the action system is prone provide insight into the operation of that system
- Examples:
  - Substitution errors suggest the target of an action is specified independently of the action
  - Omission and sequence errors appear to be incompatible with “chaining” accounts
  - Priming of actions by objects (cf. Tucker & Ellis, 1998) suggests action representations are activation-based

Routine Action: “Frontal” Apraxia

- Neurological patients with frontal damage are often prone to disorganisation of routine action
- This disorganisation resembles an exaggerated tendency towards normal slips and lapses
- Schwartz *et al*. (1998, 1999):
  - the predominant error type is omission, especially in more severe patients
  - substitutions, perseverations, intrusions and errors of manner or quality also occur

Routine Action: An IA Model

- Cooper & Shallice (2000):
  - A hierarchical interactive activation model operating in the domain of coffee making
  - Nodes correspond to action schemas of varying complexity
  - Multiple sources of activation contribute to each node
  - With appropriate weighting of each source, the model was able to generate appropriate behavioural sequences
  - An "existence proof" of the principles of Norman & Shallice's (1986) routine action control system
  - Damage simulated by modifying the relative weights of different sources of activation

Routine Action:
An RN Model

- Botvinick & Plaut (2000/submitted):
  - A recurrent connectionist model of the coffee making task
  - Network trained on a variety of well-formed coffee making sequences
  - Damage was simulated by the addition of noise
  - The damaged network showed errors similar to those of patients, including omission errors
  - The training regime was critical in shaping the model's behaviour and the errors to which it was prone

Deficits in Action Selection: Utilisation Behaviour

- Lhermitte (1983):
  - Patients with extensive orbito-frontal lesions may be inappropriately stimulus driven
  - When seated in front of a full jug and glass, a UB patient will pour into and drink from the glass, even when instructed not to do so
- UB within an IA model:
  - Inappropriate regulation of activation within the action system, leading to environmentally triggered action
- How might UB arise in an RN model?

Deficits in Action Selection: Dopamine Disorders and Action

- Amphetamine psychosis:
  - highly stereotyped behaviour
  - increased rates of responding with reduced response categories (Lyon & Robbins, 1975)
  - linked to increased activity within the dopamine system
- Bradykinesia:
  - unmedicated Parkinson's patients can show slowed action initiation, but near normal performance after an action is initiated
  - linked to dopamine depletion

Deficits in Action Selection: Modelling Dopamine Disorders

- Amphetamine psychosis and bradykinesia are both consistent with an activation-based substrate
- Cooper & Shallice (2000):
  - A qualitative simulation of basic effects through the manipulation of one parameter
  - Increasing self activation ? increased response rates
  - Decreasing self activation ? slowed initiation
- How else might these effects be simulated:
  - in recurrent network models?
  - in ACT-R?

Deficits in Action Selection: Forms of Perseveration

- Two forms of perseveration have been noted in frontal patients (e.g., Schwartz *et al.*, 1991):
  - Continuous: immediate repetition of a subtask
  - Recurrent: repetition of a subtask after an interval
- Hymphreys & Forde (1998):
  - Two patients with extensive frontal lesions
  - Patient HG: mainly continuous perseverations
  - Patient FK: mainly recurrent perseverations
  - Conclusion: Continuous and recurrent perseveration have distinct origins

Deficits in Action Selection: Forms of Perseveration

- Within IA models, perseverative errors may arise from deficiencies in “rebound” inhibition:
  - Continuous perseveration: RI is insufficient to disengage the current response
  - Recurrent perseveration: RI is sufficient only to cause a temporary disengagement of a response
- How might different forms of perseveration arise within ACT-R?
  - Kimberg & Farah (1993): weakened associative links
  - Goal decay (cf. Goal neglect: Duncan, 1995)

Routine Action: Monitoring and Error Correction

- Humphreys *et al.* (2000):
  - Normal subjects were required to perform several everyday tasks whilst carrying out the Trails task
  - Many action errors took the form of aborted reach actions
  - These errors generally arose immediately after making a self-corrected error on the Trails task
  - Aborted reach errors are rarely observed in neurological patients
  - Do patient errors result from faulty monitoring, which prevents false reaches from being aborted?

Monitoring and Error Correction: Models

- Cooper *et al.* (in preparation):
  - An augmented version of the Cooper & Shallice (2000) model applied to a more complex task
  - Task: approximately 50 actions with order constraints
  - Task complexities require additional machinery for controlling sequential behaviour (preconditions and postconditions)
  - These allow simple monitoring and error correction
- How might the Botvinick & Plaut model incorporate such processes?

Between Trial Effects on RT: Data (Rabbit, 1966)

- In choice reaction time tasks (Rabbit, 1966):
  - Mean RT on error trials is less than on non-error trials
  - Mean RT on non-error trials immediately following an error is greater than on other non-error trials
  - Similar results were obtained by Lamming (1968)
- Luce (1986):
  - Behaviour can be understood in terms of a shift along a speed-accuracy trade-off curve
  - High accuracy results in subjects speeding up, which results in error, slowing, and then increased accuracy

Between Trial Effects on RT: Data (Eriksen & Eriksen, 1974)

- Eriksen's CRT flankers tasks:

  Congruent trials:

  S S S S S

  Incongruent trials:

  H H S H H

- Congruent trials are faster and more accurate than incongruent trials, but also:
  - I is faster and more accurate if preceded by I than if preceded by C
  - C is faster if preceded by C than if preceded by I (with accuracy near floor in both cases)

Between Trial Effects on RT: Data (Altmann & Gray, 2002)

- Altmann & Gray (2002):
  - Two CRT tasks involving the same stimuli but a different discrimination
  - Within each block, subjects performed sequences of trials of each task
- Both RT and error rates *increased* with position in sequence
- Strengthening the most recent task cannot account for this pattern
- Altmann & Gray attribute it to goal decay

Between Block Effects on RT: Data (Tzelgov *et al.*, 1992)

- The trial type frequency effect in Stroop:
  - Decreasing the frequency of congruent and incongruent trials relative to neutral trials increases the difference between performance on those trials
  - This appears to reflect on-line adjustment of processing parameters: when incongruent trials are common the cognitive system configures itself so that the Stroop effect is smaller than when they are rare

Between Trial Effects on RT: Data (Allport *et al.*, 1994)

- Counter-intuitive effects on RT of switching between word-reading and colour-naming:
  - Word-reading is slowed when the previous trial requires colour-naming, but colour-naming is not slowed when the previous trial requires word-reading ("asymmetric switch cost")
  - When switching from colour-naming, word-reading is slower for incongruent than neutral stimuli, but there is no difference in RT between such stimuli on non-switch trials ("reverse Stroop interference")

Between Trial Effects on RT: Relevance to Sequential Control

- Robust between trial effects indicate that the processing speed of the cognitive system is affected by its recent inputs and/or outputs
- They cannot be accounted for by static systems or systems with fixed processor cycle speeds (e.g., impasse-free Soar, EPIC?)
- Botvinick *et al*. (2001):
  - Robust between trial effects reflect the modulating effects of on-line control on task behaviour

Between Trial Effects on RT: Three IA Models

- Botvinick *et al.* (2001) adapted existing (simple) IA models of Stroop, Eriksen, CRT to include feedback
- Feedback is based on a measure of conflict within the principal IA nodes in the model
- The effect of feedback is to modulate activity from different pathways in the model to reduce conflict
- In all cases, the adapted models provide good accounts of between trial effects

Between Trial Effects on RT: A Further IA Model

- Gilbert & Shallice (2002) adapted the Cohen & Huston (1994) model of Stroop to allow study of task carry-over effects
    - Connections from input units to task-set units
    - Control unit states persist across trials
  - The model accounts for the standard Stroop effects and several task-switching phenomena, notably asymmetric switch costs and reverse Stroop interference
- Claim:
  - Switch costs arise from between-task interference, and not an additional stimulus-driven task-setting process (*contra* Kieras *et al.*, 2000 and Sohn *et al.*, 2000)

Between Trial Effects on RT: Interim Thoughts

- The approach of Botvinick *et al.* (2001) and Gilbert & Shallice (2002) does not appear to generalise to the data of Altmann & Gray (2002)
- Can changes in base-level activation or association strength and decay yield appropriate between trial effects within ACT-R models?
  - Many of the changes are "rational" in the ACT-R sense (e.g., decreasing RT when errors are rare)
  - If so, ACT-R would seem to provide a more parsimonious account of the effects

Between Trial Effects on RT: Models and Neural Structures

- Botvinick *et al.* (2001) relate conflict within IA networks (and the need for feedback to reduce this conflict) to activity of the ACC
  - Does the cognitive architecture include specialised control modules, and is there an equivalent in ACT-R?
  - Is the Botvinick *et al.* account of ACC activation spurious?
- Either way, what function(s) might ACT-R attribute to ACC (and other neural structures engaged in such tasks)?

Psychological Refractory Period

- Psychological Refractory Period (PRP) effects:
  - Subjects are required to respond to two stimuli (task 1 and task 2) presented in quick succession
  - Experiments vary Stimulus Onset Asynchrony (SOA)
  - RT for task 2 is delayed, apparently until task 1 processing is complete (smaller SOA ? longer delay)
- Numerous theoretical accounts of PRP effects:
  - Bottleneck accounts
    - Perceptual, response-selection, movement-production
  - Unitary and multiple resource theory accounts

The Challenge of PRP Effects

- Successful PRP models employ production system control:
  – Meyer & Kieras (1997): Strategic Response Deferment theory of PRP effects (in EPIC)
  – Byrne & Anderson (1998): ACT-R/PM: EPIC with ACT-R as its central processor

- PRP effects appear to pose a challenge for other mechanisms of sequence generation/regulation

Other RT Paradigms: Negative Priming and IoR

- Negative Priming:
  - RT to a target item can be slowed when the target item was an ignored distractor item on the previous trial
  - NP is usually taken to imply that ignored distractor items are actively inhibited
- Inhibition of Return:
  - Responses to a target presented at a random location can be slowed if the location is cued less than 300 ms before the target appears
  - IoR is usually taken to imply inhibition of the cued location

NP and IoR: A Challenge for ACT-R?

- NP and IoR are generally interpreted as reflecting the effects of inhibitory processes, perhaps acting to disengage attention
- How might NP and IoR be accounted for within ACT-R?
- More generally, can purely excitatory spreading of activation account for NP/IoR effects?

Dual Tasking and Interleaving

- Dual tasking, interleaving and interruption handling impose further requirements on cognitive control, e.g., goal maintenance / reconstruction
- Salvucci & Macuga (2001): ACT-R/PM model of the effects of cell-phone dialling on driving
  - Individual task models modified to allow interleaving
  - ACT-R (production systems in general?) provides the necessary machinery for interleaving, but …
  - Are there generic strategies for interleaving that might be encoded via generic productions?

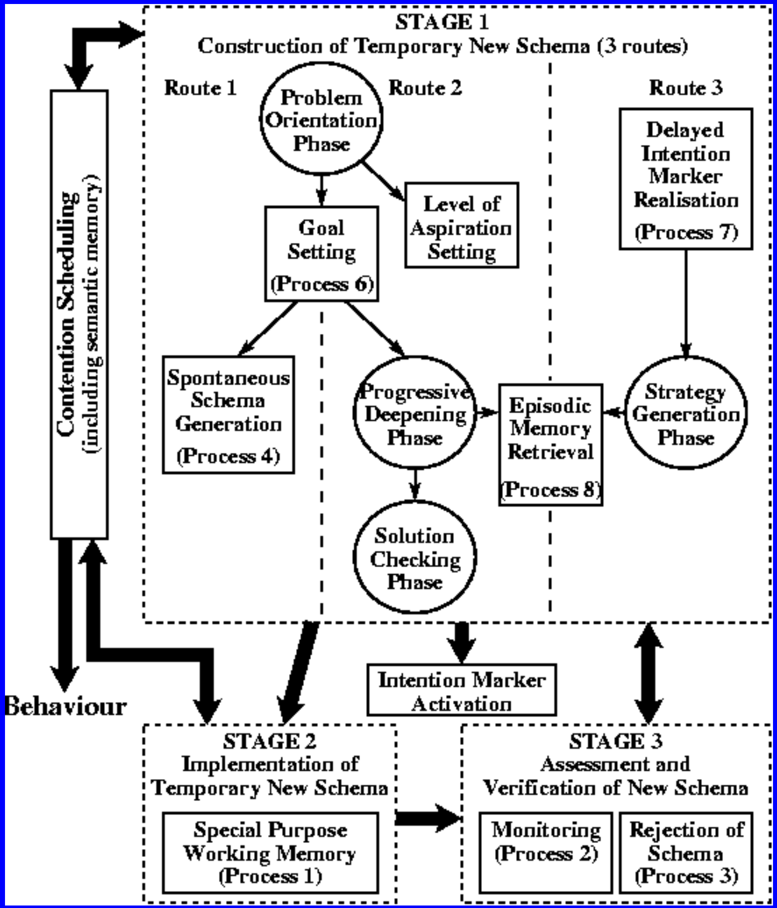
Summary of Effects and Models

- Action:
  - Basic effects accounted for by IA and RN models
  - Questions over learning in IA model
  - Questions over extending RN model to complex tasks
  - RN model unable to generate relative timing data
  - Questions over extending RN model to monitoring
- RT effects:
  - Several successful IA models
  - PRP effects: Successful production system models
  - NP/IoR: Are inhibitory interactions necessary?
- Handling interruptions and interleaving of tasks
  - Production systems provide appropriate machinery

Modularity Revisited: Alternative Views

- There is no distinction between central and peripheral processes (e.g., Wells, 1998)
  - How could peripheral processes evolve so as to provide just the right information to a central processor?
- Both central and peripheral processes are modular (e.g., Shallice, 1988)
  - Modularity is a graded concept
  - Neuropsychological dissociations reflect the breakdown of individual modules

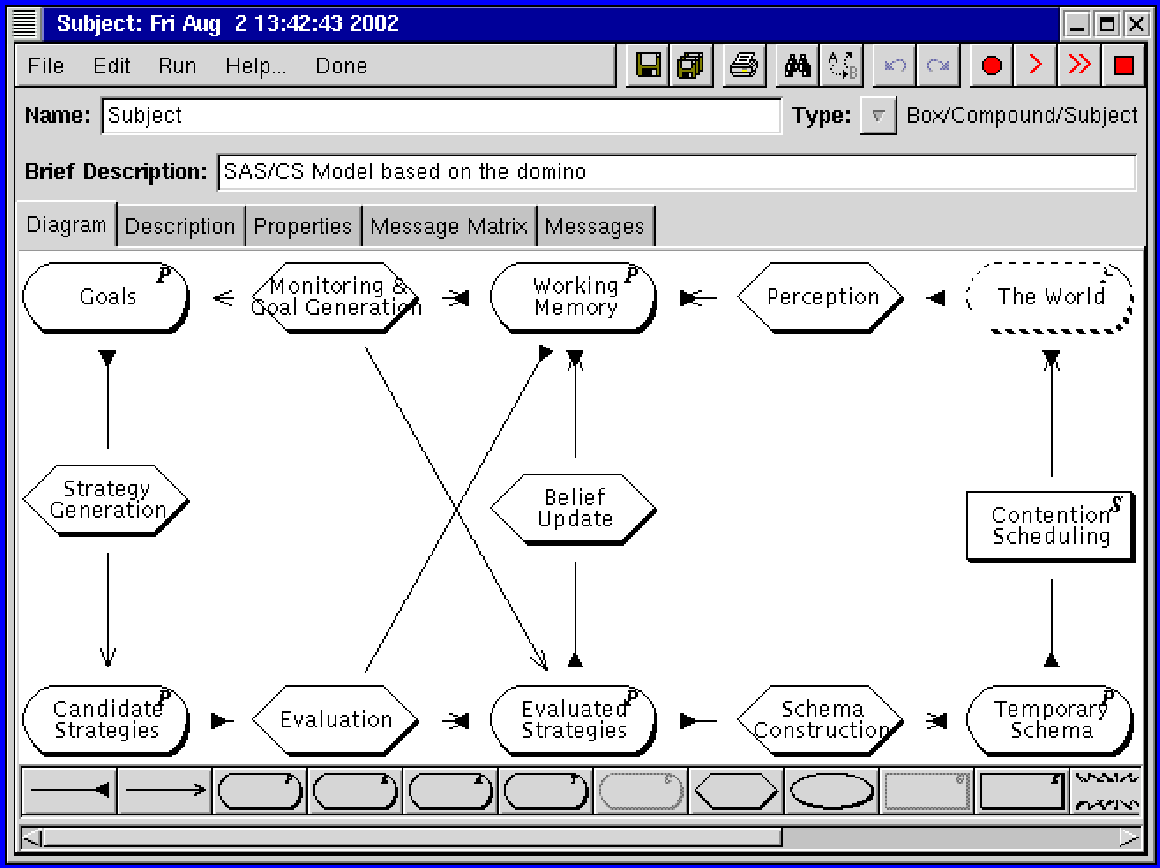
Modular Central Processes: Shallice & Burgess (1996)



Modular Central Processes: Shallice & Burgess (1996)

- Shallice & Burgess argue for various structures and processes on neuropsychological grounds
- But:
  - the diagram confuses structures and processes
  - only the contention scheduling subsystem is implemented (though see Glasspool, 2000)
  - the details of key “phases” and processes are not specified

Shallice & Burgess (1996) in COGENT



Modularity Issues for ACT-R

- Can ACT-R address neurological dissociations?
  - Early ACT-R studies of neurological deficits (Kimberg & Farah, 1993) do not address dissociations
  - Is modular organisation of productions (*a la* Newell, 1990) sufficient?
- Is there a place for generic processes such as strategy generation, monitoring, and error recovery in ACT-R?
  - Does ACT-R need default productions?

Conclusions I: Sequential Control

- IA models have been used to successfully account for most findings concerning sequential behaviour
- Recurrent network models of a range of RT phenomena have yet to be developed
- Claim:
  – On balance, the weight of evidence currently favours an activation-based substrate for the generation and regulation of sequential behaviour

Conclusions II: Beyond IA Models

- But…
  - There are some tasks to which IA models have yet to be applied successfully,
  - There is little work on learning within IA models, none on integration of different IA task models, and little on goal-oriented extensions of IA
- Is ACT-R the kind of goal-oriented extension IA models require?

Conclusions III: Issues for ACT-R

- Can ACT-R account for between-trial effects on standard RT tasks?
  - Successful IA models rely on inhibitory interactions
  - Are inhibitory processes necessary to account for RT data (Stroop interference, negative priming, inhibition of return)
  - Milliken *et al*. (1998) and Kimberg & Farah (2000) suggest not
- Can ACT-R's non-modular cognitive processor account for neuropsychological dissociations?

THE END

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