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Hatfield 0083
Email: dkourie@dos-lan.cs.up.ac.za

Subeditor: Information Systems

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Email: lintrona@econ.up.ac.za

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*Computer Society of South Africa
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Guest Contribution

About the author

Dr. Matthew Jones from the University of Cambridge (Management Studies Group) is in fact trained in the Agricultural and Environmental Sciences with a PhD from the University of Reading (1984). He currently holds the position of University Lecturer in Information Management at Cambridge.

He was the secretary and treasurer of the British Institute of Energy Economics Energy Modelling Study Group 1984-1992, member of the Cambridge Health Authority Information Strategy Group 1989-1991. He is also currently member of the British Human Computer Interaction Group, member of the DTI Human Interface Club Special Interest Group on the Organisational Aspects of Information Technology and treasurer and board member of HICOM Human Computer Interaction electronic conferencing system.

He is a highly regarded scholar and has published a

substantial number of academic papers in scholarly journals. Some of his more recent publications on business process reengineering (the topic of his contribution) are: (a) Jones, M.R. Don't emancipate, exaggerate: rhetoric, reality and reengineering. In: Baskerville, R.L.; Smithson, S.; Ngwenyama, O. & DeGross, J.I. (Eds) *Transforming Organizations with Information Technology*. North Holland, Amsterdam, pp357-378, (1994). (b) Jones, M.R. Empowerment and Enslavement: Business Process Reengineering and the Transformation of Work. Paper presented at the "New Visions of the Post-Industrial Society" conference. University of Brighton, (9-10 July 1994) (c) Jones, M.R. The Contradictions of Reengineering. Paper presented at the "Management Challenges in IS" Conference, Cranfield University, 12-13 July 1994.

Business Process Reengineering: Management's New Paradigm or Emperor's New Clothes?

Matthew R Jones

University of Cambridge, Management Studies Group, Department of Engineering, Mill Lane, Cambridge CB2 1RX, UK
e-mail: mrj1@uk.ac.cam.eng

Abstract

Business Process Reengineering (BPR) is currently attracting much attention as an approach to organisational change, but has received relatively little critical scrutiny. This paper seeks to examine the origins, antecedents and content of BPR as they are described in the main writings on the topic, in order to address three questions: Is there one form of BPR or many? Is it new? What factors may account for its popularity? Some of the criticisms that have been made of BPR are also discussed.

Keywords: *Business Process Reengineering*

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1 Introduction

Business Process Reengineering (BPR) has been described as the "hottest management concept since the quality movement" [8] and as "one of the key management concepts of the 1990s" [23]. Klein [41], for example reports that 88% of a survey of senior executives claimed that they were engaged in reengineering projects, while Cane [10] reports that up to 70% of large UK companies have un-

dertaken, or are about to undertake BPR initiatives. It has certainly also received its fair share of attention in the management literature in recent years. An on-line search using the terms "Business Process Reengineering", "Reengineering", "BPR" and "Business Process Redesign" in early 1995, for example, identified 3,592 journal, magazine and newspaper articles on the topic since 1990.

Yet, despite the huge amount that has been written about it, the concept of BPR remains elusive. Is it simply

the latest buzzword, "that people bandy around ... even if they are just putting in a new computer system" as some popular reports suggest [65], or is it the most important contribution to thinking about organisations since Adam Smith's *Wealth of Nations* as Hammer & Champy [29] claim? Is it primarily an extension of traditional time and motion studies as Parker [54] states, or of Total Quality Management as Shillingford [57] describes, or is it an entirely "new paradigm" [26]? And what is the relationship between Information Technology (IT) and BPR? IS BPR simply a way of "rebadging" existing IT products to increase sales [65], or is it one of the resources to be reengineered as Morris & Brandon [51] imply, or should IT be seen as enabling new processes as Coulson-Thomas [11] suggests, or is it the primary enabler as Davenport [13] proposes?

The confusion surrounding these questions suggests the need for a critical review of the concept of BPR; to examine its origins, antecedents and content. From this it is hoped to develop a clearer picture of the nature of BPR. Is there only one type of BPR or are there several alternatives? What is the substantive content of BPR and how much of this is new? What factors may account for the interest shown in it? This paper therefore seeks to complement the small number of critical analyses of BPR, such as Grint [25], Willmott [67] and Grey & Mitev [24] that have recently begun to emerge. It differs from them however in focusing primarily on the "theory" of BPR, such as it is, rather than seeking to locate the concept within broader social and organisational changes.

For practical reasons it should be clear that this paper cannot aim to provide a full literature review. Moreover a large proportion of the articles consist of reports (frequently quite brief) on the BPR phenomenon for different audiences, or "case studies" of BPR success (often written by the consultants involved), rather than discussions of the nature of the concept. This paper therefore concentrates on those publications widely cited as influencing the development of BPR, or offering a more extended discussion or substantial report on it.

2 Origins of BPR

A number of writers have sought to suggest that the origins of BPR go back many years. Holtham [34], for example suggests that the concept of 'breakthrough' management coined by Juran [39] is "virtually the same" as reengineering, while Bartram [3] traces the "theoretical background of reengineering" to a 1961 Harvard Business School paper on work simplification. Klein [42] even identifies reengineering projects in the Nineteenth Century and cites Henry Ford as an early exponent.

Whatever the merits of these arguments, the evidence of the on-line search of bibliographic databases indicates that the vast majority of the literature on BPR has appeared in the last five years, with 96% being published since 1992. This may be attributed to the influence of two articles pub-

lished in the latter half of 1990 in the *Harvard Business Review* and *Sloan Management Review*. Both discussed the need for companies to reorganise along process lines, exploiting the opportunities provided by developments in Information Technology.

The *Harvard Business Review* article, "Reengineering Work: Don't Automate, Obliterate" by Michael Hammer [28], a former computer science professor at MIT, is the more widely cited and is credited by many with starting the BPR bandwagon rolling. It introduced the term "reengineering" and set the tone for much later writing on the topic. The rather more academic article in the *Sloan Management Review* by Thomas Davenport & James Short entitled "The New Industrial Engineering: Information Technology and Business Process Redesign" [14], was associated with the MIT "Management in the 90s" programme [56]. This introduced the acronym BPR and also, as the title indicates, explicitly linked it with IT. The ideas in this paper were later extended by Short & Venkatraman [58] to address processes operating across the boundaries of the traditional business firm, an activity they called Business Network Redesign.

Although Hammer [28] does not actually use the term "Business Process Reengineering", and indeed has recently criticised its widespread use in association with his ideas [30], when he described reengineering as "the radical redesign of business processes" he was clearly talking about a similar activity to that of Davenport & Short. The two papers also referred to some of the same examples as illustrations of their concepts. Thus, even if reengineering and business process redesign are not completely synonymous they would appear to be sufficiently closely related (in practice, if not necessarily in principle) that the use of BPR as an acronym to describe them both would seem justified. On similar grounds, therefore, BPR will, for the purposes of this paper, also be used to describe the various process-oriented approaches to significant business re-organisation that have emerged since 1990, even though their authors may originally have employed alternative names such as Business Process Improvement, Business Reconfiguration, Business Reengineering, Core Process Redesign, Corporate Reengineering, or Process Innovation.

3 Antecedents of BPR

In his original *Harvard Business Review* article [28], Hammer did not seek to associate BPR with any theory of organisations, indeed he presented it specifically as overthrowing arrangements of work organisation that he traced back to the Industrial Revolution. Instead, his argument was based pragmatically on the experience of process redesign in two companies. Although the argument and examples were later elaborated in Hammer & Champy [29], this also does not attempt to develop a theoretical basis for BPR. Rather it was suggested that it is a "conceptually new business model" with no precursors.

Davenport & Short [14], in contrast, described BPR

as "the new industrial engineering (IE)". Earlier IE, they explain, was based on F.W. Taylor's extremely successful "mechanizing vision". This was effective in the past, they argue, because the business environment was "largely stable". In today's turbulent business environment, however, a new approach is needed. It is not clear, though, whether Davenport & Short see BPR as rejecting, transcending, or pragmatically adapting Taylorism, although it would appear that they certainly wish it to be seen as lying within the tradition of the "scientific school of management". This view would seem to be supported by Parker [54] who describes BPR as involving time and motion techniques, by Morris & Brandon [51] who associate it with "IE, time and motion, Operational Research and Systems analysis" and by Glover (quoted in [65]) who suggests that it is "upmarket O & M". Wheatley is quoted in Brown [6] as describing BPR as the "supernova" of this "mechanical view of organisations".

Although Hammer and Davenport & Short are generally acknowledged as the progenitors of BPR, it does not mean that their view of the topic can necessarily be seen as definitive. BPR is a commercial product as much as a theory of work organisation. For the customer of BPR, therefore, it is the approach they buy which is likely to define it for them, even if this does not conform to Hammer or Davenport & Short's model. Thus, for example, despite Hammer & Champy's emphatic statement that Reengineering is not "the same as quality improvement, total quality management (TQM), or any other manifestation of the contemporary quality movement" [29], Shillingford [57] describes BPR as "often evolving out of a TQM initiative" and suggests that its rationale is that "concepts like Japan's 'best manufacturing practice', which uses Just-in-time techniques, can be applied to the office as well as the factory". This view is not a simple misunderstanding, but is based on the approach to BPR developed at Rank Xerox, who were selling it, with accompanying software tools, as a consultancy service (at a starting price of \$100,000) [22]. The association of BPR with TQM is also made by Johannson *et al* [36] and *inter alia* by Davenport [13], while Earl [19] and Mumford [52] link it with lean production [68].

Other writers have identified BPR with a number of different organisational and technical developments. For example Coulson-Thomas [11] links it to the emergence of the "network organisation", Stewart [59] to the "horizontal organisation" [53] and Kaplan & Murdock [40] to Dichter's vision of the organisation of the 90s [17]. More bluntly, Byrne [8] suggests that BPR can sometimes be seen as "little more than a euphemism for laying people off", and it is certainly recognised in the popular BPR literature that part of the interest in it comes from companies seeking to reduce staff numbers in the face of economic recession [65]. In some reports BPR is also linked with the implementation of specific types of technology, usually image processing and workflow systems for office automation [57].

Given that the theoretical antecedents of BPR may be expected to be reflected in the approach adopted, i.e. those

seeing it as an extension of TQM may be expected to draw on techniques and social structures historically associated with Quality programmes, then this diversity of views on the source of BPR thinking could suggest that there are several distinct versions of it. Another possibility is suggested by Davenport [13] who argues that Process Innovation, as he calls it, does not have a single source, but has developed from the combination of five different approaches to business improvement. He identifies these precursors as: the quality movement, industrial engineering (and its offshoot the soft systems movement *sic*), the socio-technical school, the technology transfer literature and the IT for competitive advantage literature. Even if it is accepted that these approaches can practically be combined, however, it is possible to question whether such a mixed pedigree would seem any more likely to yield a consistent approach to BPR than the various different precursors on their own.

As has already been noted, however, BPR is not just a theoretical construct, but a guide to practical organisational intervention. Whether BPR's theoretical antecedents are consistent, or even what they are thought to be, may not matter in practice, therefore, if what is actually advocated is the same for all the different 'versions', or at least sufficiently similar that a common approach is likely to be adopted. The next section will therefore consider the content of BPR as it is presented by a number of different authors to see if they share a common view of what BPR involves.

4 Content of BPR

There have been many attempts in the BPR literature to define the concept, not least by Hammer & Champy [29] who devote a whole chapter of their book to an elaboration of their statement that it is "the fundamental rethinking and radical redesign of business processes to achieve dramatic improvements in critical, contemporary measures of performance, such as cost, quality, service and speed". Unfortunately, few of the definitions show more than a limited consensus on its key features, particularly when the terms employed are examined in more detail. While some of the differences revolve around distinctions that would probably have appealed to mediaeval theologians, others mark more significant divisions within the field.

Process orientation

Perhaps the only real common ground between all BPR approaches is their view of organisations as being made up of *processes*. Hammer & Champy [29] define a process as "the collection of activities that takes one or more kinds of input and creates an output that is of value to the customer". This is contrasted with the traditional perspective which sees organisations as made up of separate functions (such as marketing, finance, sales and so on), typically located in their own specialist departments.

While agreed that BPR involves a focus on processes, there is disagreement in the literature about their scope.

There would appear to be four different "levels" at which these may operate. At the lowest level there are individual work tasks, such as customer inquiry handling, which combine various different, if simple, activities. At the second are work processes which may operate within a single functional department. At the third level the processes operate across departments within an organisation, and at the highest level they are inter-organisational. Each of these are, in principle, compatible with Hammer & Champy's definition, particularly if we take the currently popular view of organisations as markets, in which customers may be internal as well as external.

Harrington's concept of a business process which he defines as "all service processes and processes that support production processes" [31] would seem to operate at the first two levels, that is, within established departmental boundaries. Similarly, Morris & Brandon [51] define a process as "larger than a task ...[but] smaller than an area of business such as operations, human resources or shipping", while Hall *et al* [27] state that "a process can be as narrowly defined as a single activity in a single function". Davenport & Short [14] also talk of redesigning "interpersonal processes" which "involve tasks within or across small workgroups typically within a function or department". Hammer & Champy [29], however, suggest that processes to be reengineered typically operate across traditional functional/departmental boundaries, a view shared by Johannson *et al* [36] and Davenport [13] amongst others. BPR, Hammer & Champy argue, involves "breaking down the functional silos" and Davenport [13] states that "adopting process innovations inevitably entails cross-functional and cross-organizational change". Although these writers also allude to the possibility that processes may cross organisational boundaries, this is the particular focus of Venkatraman [64] who talks of "business reconfiguration" and Short & Venkatraman [58] who discuss "business network redesign".

Scale of change

Partly related to the scope of processes is the question of the scale of change, both in terms of extent of reorganisation and the performance improvements sought. Hammer & Champy [29] argue for a resolutely radical approach, describing re-engineering as a "new beginning", a "blank sheet of paper". As Hammer [28] puts it "the point is not to learn what happens to form 73B in its peregrinations through the company, but to understand the purpose of having form 73B in the first place". Thus BPR, Hammer & Champy argue, means "discarding existing processes and replacing them with entirely new ones" so as to achieve a "quantum leap" [in performance]. This view is shared by Johannson *et al* [36] who argue that organisations should be aiming not just for marketplace parity, but for "market dominance". This requires them to "break the china", "to challenge the very purposes, principles and assumptions on which their business is based". Davenport & Short [14] also talk of "fundamental reshaping" and Davenport [13] of "effecting creative and radical change to realize order-of-

magnitude improvements". Similarly, Heygate [32] argues that managers have to be "immoderate in their ambitions to improve processes", while Hall *et al* [27] argue that "effective transformation ... requires a clean slate approach to process redesign".

Other writers, in contrast, appear to envisage a more modest, evolutionary activity. Harrington [31], for example, describes BPR as involving the "improvement of inefficient processes" and this is echoed in Fintech [23]. Glover, quoted in Warren [65], also argues that "radically changing the whole ethos of the business may not be necessary: there may be just one division which needs attention". Morris & Brandon [51] do not specifically discuss the scale of change, but the general absence of the revolutionary rhetoric characteristic of Hammer & Champy [29] suggests that their approach is also more incremental.

This point has recently shown signs of becoming a point of serious schism in the BPR literature. Thus as, Yates [70] reports it has led to a parting of the ways between Michael Hammer and James Champy. Hammer, for his part, likens reengineering to an organisational "neutron bomb" and argues that "trying to do a little bit of reengineering is like trying to be a little bit pregnant". Champy, in contrast, argues that "there are good things that we don't want to destroy ... there is a sense of pragmatism in older managers that I don't think companies can afford to lose". Davenport has also criticised "the myth of the clean slate", arguing that "designing with a dirty slate will often yield a more implementable process" [15].

The means of achieving BPR

Another difference between BPR approaches relates to their ideas on how it should be achieved. Thus, while most writers specify a methodology for conducting BPR, Hammer [28] offers only a set of principles which the exercise should seek to pursue. Even in Hammer & Champy [29], there is no specific method, rather there is a discussion of outcomes, of the roles involved, case studies of the "experience of process redesign" in several companies and a discussion of the most common errors that lead to reengineering failure. Avoid these it is argued "and you almost can't help but get it right".

It would seem clear therefore that Hammer wishes to avoid a formulaic approach to BPR and sees it as a way of thinking and achieving radical organisational change rather than as a rigorous procedure to be followed. This may be contrasted with the recommendations of Morris & Brandon [51] and Booz-Allen & Hamilton [5] who argue that the use of a systematic methodology is essential for BPR success (even if, on closer examination, this often turns out to be a set of vague guidelines of limited practical utility). This view appears to be particularly prevalent in the information systems and industrial engineering literature on BPR (see for example, [26, 42, 66]). Klein [43] suggests that these positions represent two different schools of thought on the approach to BPR which he calls the "intuitives" and "methodologists" and identifies the particular consultancy companies associated with each.

The role of information technology

A potentially important area of disagreement between the different BPR approaches, as was noted in the introduction, is the contribution of IT. Two different roles for IT need to be distinguished here: firstly its use as a tool for the support of the BPR activity, and secondly its position as an axial principle around which the redesign of business processes should be planned. Davenport [13] calls these two roles "IT as implementer" and "IT as enabler" though there are some problems with this terminology as is discussed below. With respect to the first of these there would seem general agreement that BPR may be usefully supported by IT-based tools and some approaches explicitly recommend their use. For example, Morris & Brandon [51] give considerable attention to the use of simulation to test new process designs and identify it as a specific stage in their method, and Davenport & Short [14] discuss the use of CASE tools in drawing process models. Others discuss BPR activities which involve IT support. For example Sutherland [61] discusses the use of "reengineering laboratories" which make use of a variety of IT systems, while Heygate [32] suggests that "the role of IT in building individual's skills may well prove to be the most valuable application of information technology so far discovered".

On the question of whether reengineered processes should be based on the use of IT, however, there would appear to be a significant divergence of opinion. A number of the key writers, such as Davenport & Short [14] for example, see IT as playing a central role in BPR, making the consideration of IT "levers" one of the five stages in their BPR method and describing as an exemplar a case of "IT-driven process redesign" at Xerox. Similarly, Guha *et al* [26] talk of "IT-induced reengineering". The concept has also been picked up by a number of IT/IS consultants who present it as a new approach to applying IT in organisations. For example Heygate & Brebach [33] explain how their "decision engineering, [IT-supported] organisational flattening, technology scan and IT cost estimation" techniques can support an "IT-driven business strategy", and Aikins [1] discusses how BPR can make use of knowledge-based systems. In some cases BPR is even associated with specific types of IT, usually workflow software and document image processing [57]. These writers would therefore seem to share Davenport & Short's view that IT and BPR "have a recursive relationship ... each is the key to thinking about the other" [14]. From this perspective IT needs to be considered in the early stages of redesign so that "awareness of IT capabilities can – and should – influence process design" [14].

Other writers, however, argue that "BPR and IT are certainly not synonymous" [61] and that "in theory, BPR does not have to involve IT at all" [23], rather it is "the common-sense practice of redesigning business processes before bringing in technology" [21]. Harrington [31], for example, does not mention the use of IT and confines discussion of the use of computers to a section on "automation". Morris & Brandon [51] also state that BPR "is not an IT topic", while Rowland [55] argues that "those who

say that IT is a requirement of BPR have missed the point". This does not mean that these writers deny that IT may contribute to BPR, but rather that they believe that process design should precede consideration of IT options. For example Shillingford [57] states that "[o]ne attraction of BPR is that it makes IT subordinate to business objectives ... in most cases 80% of the value of BPR comes out of examining the way things are organised ... [o]nly 20% comes from IT".

An intermediate position appears to be that IT can "enable" new ways of carrying out processes and that redesign should therefore "be undertaken with a full knowledge of how technology can help" [5]. Hammer & Champy [29], for example, devote a chapter to illustrating that shared databases, expert systems, telecommunications networks, decision support tools and so on, "break the rules that limit how we conduct our work" and that IT is therefore a "part of any reengineering effort" whose importance it is "difficult to overstate". This argument, however, smacks rather of technological solutions in search of suitable applications rather than a convincing case that the use of IT is an essential feature of any reengineering activity as they suggest. It may be contrasted, for example, with the statement by Holtham [34] that "very few of the successful case studies of BPR have been initiated out of the new opportunities offered by IT ... the development of technologies such as workflow, groupware or document image processing have no *a priori* connection to the need to reengineer business processes". The concept of IT as an "enabler" may therefore be rather closer to the IT-led position taken by Davenport & Short [14] than might at first appear to be the case.

It is also possible, however, to exaggerate the differences between authors on the role of IT. Thus, as has been noted, those who see IT as secondary may also discuss how it can "make it possible for processes to be carried out in a new way" [23], while the proponents of IT-driven approaches will emphasise that BPR requires a "carefully-considered combination of both technical and human enablers" [13]. The vagueness of terms such as "enabler" means that it is almost impossible to tell whether there is a real difference of interpretation in either theory or practice between the writers, but it would seem reasonable from the context in which these terms are used that there is at least a difference of emphasis.

5 Discussion

Having considered the content of BPR, attention may now be turned to the three sets of questions identified in the introduction to this paper for which it was hoped to find answers. Is there only one type of BPR or are there several alternatives? What is the substantive content of BPR and how much of this is new? What factors may account for the interest shown in it? Each of these will now be considered in turn.

One BPR or many?

The analysis of the literature would seem to suggest that BPR is not a unitary concept (and it would have been perhaps more surprising to find that it was). However, if each approach is not to be classified as a separate version depending on the particular context in which it is applied, then the distinctive characteristics of BPR, or of certain recognised versions of it, need to be identified in order to develop an appropriate categorisation. This raises the problem of which approaches should be recognised as legitimate. While precedence might suggest that the approaches of Hammer [28] and Davenport & Short [14] should be seen as definitive this would seem unsustainable on practical grounds if nothing else. Thus, despite the efforts of CSC Index, the consultancy with which Hammer developed reengineering, to register "business reengineering" as a trademark, this cannot prevent other companies from selling approaches, which might be quite different from that envisaged by Hammer, under a slightly different name. Nor will it stop others from describing projects as reengineering, even if they bear little resemblance to Hammer's description. This is evident from the literature (see for example [2, 18]) where analyses of "BPR success" refer to widely varying initiatives, many of which did not even describe themselves as reengineering.

A second problem with categorising approaches concerns how closely they need to correspond to an archetype to be classified as belonging to a particular version (or even to be excluded from the concept altogether) and how this might be assessed. For example two approaches may share a strong emphasis on the role of IT (assuming there is some reliable measure of strength of emphasis), but differ on the importance of a definite methodology (which again may be very difficult to define). It would therefore seem difficult to provide a robust basis on which to classify different forms of BPR.

An alternative perspective is put forward by Davenport [13] who suggests that, rather than discrete "schools" of BPR, there is a continuum of approaches between two extremes of "process improvement", an incremental, continuous, bottom-up approach, and "process innovation" which is radical, IT-led, one-off and top-down. Talwar [62] suggests a similar spectrum, from "process improvement" through "process reengineering", "business reengineering" and "transformation" to "ongoing renewal". While this takes account of the observed differences between approaches, it assumes that they vary consistently along all dimensions. In practice, this would not appear to be the case. For example, Johannson *et al* [36] might appear to be a good example of Process Innovation with their emphasis on radical organisational change. However they clearly view their approach as originating with TQM, and see IT as only one among a number of transformatory factors.

It would seem therefore that it is likely to be impossible to agree a precise definition of BPR that does not exclude some of the approaches that have been associated with the concept, or to identify a limited number of distinct versions. It may thus be best to regard BPR simply as an umbrella

term for a set of process-oriented approaches to significant organisational change.

What's new?

The limitations of such a broad, inclusive definition of BPR are obvious, however, when considering the possible novelty of the concept. For example, most of the literature acknowledges that process thinking has been at the heart of the "quality revolution" and Morris & Brandon [51] also state that the techniques on which they claim BPR is based (IE, time and motion, Operational Research and Systems analysis) "have all been concerned with processes for several decades".

If the core idea on which BPR is founded is shared with many other techniques, then what is the basis for claiming that it offers something significantly different from the others? What is to say that it is not simply a well-marketed repackaging of them? One of the key themes of a substantial proportion of the BPR literature which might therefore be a novel feature, is the contribution of IT. Certainly, the BPR literature typically lays considerably more emphasis on IT than a number of the concepts, such as TQM and "Excellence", that immediately preceded it.

The idea of IT as a "driver" of organisational change, however, goes back at least to Leavitt & Whisler [47]. Moreover, even if it is claimed that recent technological developments have made existing uses of IT more effective and provided opportunities for new and more significant interventions, the precise role that IT should play is a source of considerable disagreement amongst writers on the subject. It would thus seem an unsatisfactory basis for defining the unique character of BPR, particularly as many of its proponents are seeking to move away from the sort of technocentric viewpoint that such a definition would imply.

The remaining distinctive feature of BPR would therefore seem to be the scale of the change involved. As has been noted, however, there are some authors who do not seem to share the enthusiasm of Hammer & Champy [29] for "fundamental rethinking and radical redesign". Even if it were possible to exclude these faint-hearts from associating their approaches with BPR by some mechanism, though, this would still not resolve the problem of how the scale of change is to be measured and how the boundary between BPR and the other process-oriented techniques could be defined. For example, does BPR only describe approaches which seek change across organisational boundaries? If so, how many boundaries need to be crossed? All? More than one? Should change be measured by intent or by outcome? If the former, then BPR risks being discredited by approaches which promise more than they can deliver. If the latter, then a way is needed of separating out the contribution of the BPR activity to the outcome, from those due to other changes which may have been going on at the same time. For a variety of reasons therefore, it would appear that scale of change also does not provide a reliable means of defining BPR.

The final way in which BPR might be argued to be novel is its particular combination of process thinking, cre-

ative use of IT and radical organisational change. While there may be some practical value to this viewpoint in terms of enabling BPR writers to differentiate their approach from other techniques by emphasising some particular aspect of this combination as it suits their case, the analysis of the literature would seem to suggest that the degree of variation on each of these dimensions is so great that 'novelty' of BPR would vary from approach to approach.

This would seem to suggest, therefore, that despite BPR being widely hailed as a distinctive new contribution to management thinking (the endorsement of Hammer & Champy's book by no less an authority than Peter Drucker would suggest that this view is not confined to just a few cranks), it seems very difficult to identify clearly what it is that makes it so significant. In large part, this problem stems from Hammer's definition of BPR in terms of practice. In the absence of any explicit, new theoretical principle on which the concept may be said to be based, Hammer requires BPR to be judged by the actions it gives rise to – if it achieves new forms of organisational behaviour which significantly improve organisational performance in some agreed way, then it is a significant new technique. As has been noted, however, this does not provide the basis for an unambiguous definition of the term. Moreover, as Grint [25] points out, all of the changes that Hammer & Champy [29] identify as characterising the "new world of work" in the reengineered organisation have been proposed by earlier writers. Thus even the changes in organisational behaviour associated with BPR may not be new either.

In the traditional interpretation of Kuhn's theory of scientific revolutions [44], therefore, it would seem difficult to argue that BPR constitutes a new paradigm, since it does not offer a new perspective on organisations which differs radically from TQM and other improvement programmes that preceded it. In Lakatos' terms [45], both appear to be operating within the same Scientific Research Programme. It could hardly be claimed, moreover, that TQM, for example, has not been extremely influential in changing management thinking and that BPR was thus in some way a conceptual Copernicus building on the unrecognised contribution of TQM's Tycho Brahe. Yet, if it is accepted that the immense interest shown in BPR is based on something more than self-delusion, then we need to provide some explanation of what this particular Emperor is wearing, even if it does not seem possible to define this in absolute terms.

To do so, however, would seem to require a reassessment of the nature of imperial regalia, to argue that the Emperor's old clothes were equally insubstantial. TQM, Taylorism or any of the other techniques which we may wish to consider as underlying earlier forms of organisational practice are/were, just as much as BPR, based on a set of socially-sustained beliefs which may or may not have had 'real' substance, but which depended on continuing faith in their efficacy. This is not simply a sleight of hand, but is based on the analysis of science and technology developed by Callon [9], Latour [46] and others which suggests that even in the so-called "hard" sciences, knowledge is not "discovered" in an external "reality", but is con-

structed through the recruitment of a network of allies who underwrite a particular viewpoint. Paradigm shifts therefore result from the ability of concepts to recruit the most influential allies. In this, rhetorical power may be rather more important than the "truth" of their views. The final question (why is BPR so popular?) may therefore help us to understand the allies that Hammer and Davenport & Short have, wittingly or otherwise, recruited and hence how BPR has come to have such an impact on current management thinking.

Why is BPR so popular?

The answer given by Hammer & Champy is that corporate America (*sic*) is facing a crisis, which they characterise in terms of three Cs – customers (who are taking charge), competition (which is intensifying) and change (which is becoming constant). Solutions are needed to enable companies to succeed in this new world of business. BPR, they argue, is the only technique which is capable of providing one.

Whether or not it is accepted that this crisis is real and enduring, for example Wood [69] questions similar claims made in relation to the flexibility debate, the concept that the business environment has recently become significantly more unstable and that substantial organisational change is unavoidable, appears to be widespread, particularly in the US, at present. BPR therefore appears to capture the spirit of the times in proposing that a totally new approach is needed. Such a viewpoint may also be seen as serving to legitimate the adoption of radical measures. If the company cannot hope to survive without complete re-organisation and the shedding of "armies of unproductive workers" [28] then these become a necessary price to pay. Thus, as Dixon *et al* [18] comment, "a crisis – real or perceived – may be necessary to create the conditions required to attempt a reengineering effort".

As Hammer & Champy observe [29], though, they are not the first to have diagnosed a crisis or to have suggested the way out of it. Many other techniques, from "management by objectives ... [to] ... one-minute managing" have been put forward in the past. None of them, however, "has reversed the continuing deterioration of America's corporate competitive performance". This is taken by Hammer & Champy as evidence that they were passing fads which "have only distracted managers from the real task at hand". The failure of these techniques is therefore used to bolster the case for BPR.

Paradoxically, these earlier techniques also help to sustain BPR. Thus, for example, the notion that new solutions have to be continuously invented provides a reason for looking to reengineering. The precedents for process-based techniques, even if they have not been particularly successful, also provide legitimation for the reengineering approach. In particular, the continuing influence of TQM, despite Hammer & Champy's dismissal of it, means that process-thinking may be seen as a distinct element in the network.

Hammer & Champy's particular focus on the prob-

lems of US companies may be seen as the recruitment of US patriotism as another ally. Thus they write that reengineering is "not another idea imported from Japan", but "capitalizes on the same characteristics that have traditionally made Americans such great innovators". Rather than "try to change the behaviour of American workers and managers" it "takes advantage of American talents and unleashes American ingenuity".

The success stories are another important element of the BPR network, serving both to affirm the potential of the technique, but also to associate it with the named corporations. Thus the 'hard facts' of the performance improvements cited by Hammer & Champy provide quantitative support for their claims which are thereby reinforced against sceptical questioning. Moreover the 'fact' that Ford, Bell Atlantic or Hallmark cards have successfully adopted reengineering provides powerful evidence of its value. Other case-study companies may be less well-known, but their inclusion shows that it is effective for all organisations not just those in the premier league.

Success stories also relate not just to the effectiveness of the technique, but to those who sell it. For example the near sixfold increase in the revenues of CSC Index in the last five years, is said to have "propelled [it] ... to the forefront of the [US management] consulting business" [8]. IDC [35] estimated a world market for BPR of \$230 million in 1993 which they suggested was growing at 46% per annum.

These sorts of claims and figures draw in a variety of human actors to the reengineering network. Clients would seem likely to be attracted by the chance of order of magnitude performance improvements. As more leading companies adopt BPR, the need for others to join the bandwagon would seem likely to increase, both to show themselves to be up with the latest developments and to ensure that potential benefits are not lost.

For executives of the many companies which, in Hammer & Champy's words are "bloated, clumsy, rigid, sluggish, non-competitive, uncreative, inefficient, disdainful of their customer needs and losing money", the message that BPR provides the way out of this situation would seem a very seductive one. Hammer & Champy's insistence on the need for charismatic leadership of a firmly top-down process may also be expected to be attractive to those whose position this reinforces or who aspire to such roles. Similarly, those working in IS and/or Industrial Engineering may be expected to be attracted by the prominence given to their role in many versions of BPR.

For management consultancies looking for new opportunities, the size and relatively under-developed state of the BPR market (giving low entry barriers, few established players and significant scope for product differentiation) would seem to have considerable potential. The investment being made by the major consultancies in developing BPR products illustrates their recognition of this potential [63], but also serves as a signal of reengineering's importance to competitors and clients.

For IT consultancies BPR provides both an opportu-

nity and a threat. If a suitable "front-end" product can be developed then there may be opportunities to capture market share in a new and rapidly-expanding area. Those who fail to offer BPR services, however, may find that part of their market has been sequestered both by traditional competitors who have taken the initiative and by new entrants from the management consultancy field. By getting in early on the BPR act, IT consultancies may also be able to strengthen the links between IT and BPR and thereby increase the size of their market.

The effectiveness of BPR as a management concept may also be due not just to the claims it makes, but to the way it makes them. As Jones [37] discusses, the violent language adopted by Michael Hammer, with its talk of "don't automate, obliterate", neutron bombs and grinding and frying out organisational fat gives the concept a strongly macho flavour. The apocalyptic rhetoric of organisational redemption through destruction of old habits and the adoption of pure, new processes also has biblical overtones. This is echoed in the comments of Stewart [59] who describes Hammer as "reengineering's John the Baptist, a tub-thumping preacher" and by Hammer himself who talked of reengineering as a "theology because it requires a belief that there is a new way of doing things ... it requires faith" (quoted in [7]).

Finally, it may be argued that process thinking itself simply has a considerable intuitive and practical appeal. Whether positive associations with the Quality movement are made explicitly or not, for individuals accustomed to a traditional functional perspective on organisations it can be seen to constitute a good example of an "interesting proposition" in terms of the classification scheme of Davis [16]. Thus it suggests that what had traditionally seemed to be a phenomenon that functioned effectively as a means to an end, ie the division of labour along functional lines to encourage the development of specialist expertise would ensure maximum organisational performance, was in reality a phenomenon that functions ineffectively.

6 Fad, Failure or Fatally Flawed – The Future of BPR?

This diverse network of allies recruited by BPR may help to account for its current position as "the hottest trend in management" [60]. Not surprisingly perhaps, it has also attracted many detractors. Thus Talwar [62] describes BPR "as the most fashionable and potentially the most detested management concept of the 90s". Many of these critics seek to show that BPR is simply a passing fad whose fall will be almost as meteoric as its rise. Holtham [34], for example, provides a timetable for the BPR lifecycle which predicts its demise in 1996-98. Those who dismiss BPR in this way generally adopt two lines of attack: arguing either that it is nothing more than a rebranding of existing concepts, or that its success owes more to skilful packaging than to any substantially new contribution to management thinking.

As has been discussed, the case for doubting BPR's novelty is fairly strong. The particular reasons offered by different authors for arguing that "we have seen it all before", however, often provide more insight on their own background than on the theoretical antecedents of BPR. Thus IS people see BPR as a reworking of systems analysis, industrial engineers as an extension of O&M and quality experts as a rebadging of TQM concepts. There can also sometimes appear to be an element of defensiveness in such arguments that suggests that the authors see this upstart concept as a threat to their expertise (and lucrative consultancy opportunities?).

Criticisms of the hype surrounding BPR also have some validity. As many authors note, the concept has clearly become one of the key management buzzwords of the 1990s and there is plenty of evidence of a bandwagon effect in operation. Stewart [60] even reports one telephone company executive as stating that "if you want to get something funded around here – anything, even a new chair for your office – call it reengineering on your request for expenditure". Such attitudes, however, do not necessarily prove that BPR is not a significant development. Thus, while it is possible to criticise the particular rhetorical style adopted by Michael Hammer, BPR is certainly not unique amongst management concepts in being promoted in such robust and evangelical terms. Indeed as Eccles & Nohria [20] have argued, effective use of rhetoric is an important aspect of successful change management. Moreover, as Hammer & Champy [29] are keen to argue, the proof of the reengineering pudding is in the eating.

This may help to explain why Hammer & Stanton [30] so vigorously contest what they see as the mythology of reengineering failure, arguing that the widely-cited figure of 70% was made up by Michael Hammer, based on experience with early reengineering projects. Now that the concept is much better understood, it is suggested, there is "little excuse" for companies to fail. If they do, it is because they fail to apply it correctly. This view is implicitly supported by a thriving sub-genre of the BPR literature which describes how to ensure reengineering success (see for example [4, 27]). Unfortunately, the empirical support for these recommendations, as with much of the writing on BPR, is generally weak and their prescriptions often amount to little more than 'be a successful company and do it right'.

Moreover, even if they do not fail completely, BPR initiatives may deliver less than is promised by their proponents. Thus Moad [49] reports that the benefits obtained from BPR projects intended to increase revenue were rated as achieving only 2 on a scale from 1 to 10, and even the best scored just 5 out of 10. James Champy is also reported as conceding that 30–40% of BPR initiatives "disappoint" [48]. A further interesting slant on this question is provided by Craig & Yetton [12] who point out that the rewards from an incremental improvement programme over a number of years may exceed those of a one-off radical change programme (and with less risk).

The claim made by Hammer & Stanton [30] that "the

fault [for reengineering failure] lies not in reengineering, but in ourselves" may also be challenged on more substantial grounds. Thus, as Jones [38] discusses the BPR concept may be seen to have many internal contradictions. One of these is neatly illustrated by King [41] who notes that "the most problematic aspect of reengineering is that people are often asked to be creative so that their jobs (or those of their colleagues) can be eliminated or drastically changed". Similarly, Wheatley (quoted in [6]) argues that reengineering will inevitably fail as its top-down, mechanistic approach stifles learning and creativity.

Does this mean therefore that BPR is past its sell-by date and that forward-looking organisations should seek elsewhere for their inspiration? Eccles & Nohria [20] argue that the perceived failure of established management concepts is a necessary precursor of the emergence of new "solutions". The "open season" for BPR critics noted by Hammer & Stanton [30] may therefore be an ominous sign for the concept's longevity. The on-line search also indicates that there has been a significant decline in the number of BPR-related articles since mid-1994. However, despite a number of papers discussing what is "beyond" reengineering [15] or "after" it [50], the absence, as of early 1995, of any obvious successor that is capturing the management imagination, suggests that reports of its imminent demise may be premature. Moreover, unless organisations are to be caught up in a continuous cycle of change for change's sake, and are to learn nothing from past experience, then it is important that the valuable elements of BPR are not lost, even if the label itself becomes out-dated. It is hoped that the analysis provided in this paper, may help in identifying these elements.

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Editorial

What is a good contribution?

The work of refereeing is a thankless task that infringes on the limited time of those who are best in the field. Nevertheless, it is important since the quality of refereeing does significantly impact on the quality of the final product. In order to be fair to those limited and committed referees involved, I am of the opinion that we need to become more discerning in what we put before them. There is, of course, the important role of a journal (especially so with SACJ) to assist young researchers to develop their skills by getting feedback from competent reviewers in the field. However, one must not "abuse" this privilege by sending anything "just in case"—it is the academic responsibility of the authors to ensure that the paper submitted is of high standard.

What, then, is a good contribution? A good contribution has essentially three dimensions [1]: relevance, rigor and impact—of which relevance is the most important. Although these dimensions were formulated in the context of a discussion on Information Systems research, they may also have relevance for Computer Scientists. To assist potential authors in assessing their contributions (in the making), here are some questions, steps or criteria that should clearly and explicitly be addressed before submitting a paper to SACJ.

Relevance

- Who is the target audience of influence (IS managers, system designers, educators, etc.)?
- What is the concern in the target audience that the paper addresses?
- Why is this a concern in the target audience?

Rigor

- What is the wider intellectual context of the study? Place it in this wider context.
- What other disciplines (or fields within the discipline) have studied or are concerned with the problem in the paper?
- What is the best research methodology for this problem domain?
- Why is the proposed research methodology selected?
- What question/problems may a referee raise and how are they being addressed?

Impact

- What contribution is the paper making? Is this clear and explicit in the conclusions?
- Why would a practitioner want to read the paper?
- What would a top scholar in the field say about the paper?

- Would a supervisor recommend the paper to his student(s)?
- Why can the journal not afford to publish the paper?

Clearly all of these questions may not always be equally relevant, and there may be others that could be relevant in assessing the contribution of a paper. Nevertheless, potential authors should rigorously critique their contributions and not merely "dump" material for publication. We owe it to ourselves and to the community at large.

News

Readers and contributors will be interested to hear of various plans for SACJ. These have evolved during a series of meetings held between editorial staff and available members of the editorial board and are briefly outlined below.

- Much time has been spent discussing whether or not SACJ should have a particular and/or exclusive focus. Should it seek a niche market, such as only publishing articles dealing with IT and development? Our deliberations have led us to reject such an exclusive focus. Instead, SACJ will build on its traditional role of being primarily, but not exclusively, a platform for IT researchers in South Africa. In addition, the editorial staff intends widening horizons by actively recruiting contributions, primarily from other Southern African countries, but also from countries elsewhere in Africa. While SACJ will thus continue publishing a miscellany of articles that reflect the local status of IT research, it hopes to be a vehicle that encourages, stimulates and eventually reflects research on the African continent as a whole.
- SACJ specifically encourages contributions that synthesise existing research results, such as survey articles, reviews and taxonomies. Where such articles are of significant scope, they are important for research. They will therefore be placed in the research section of the journal and may, in consequence, be submitted to the Department of National Education (DNE) for subsidy purposes.
- In order to sharply differentiate the research section from the non-research section of SACJ, page numbers in the Communications and Reports section will henceforth be preceded by an A. This is intended to signal that articles in the Communications and Reports section should not be submitted to the DNE for subsidy purposes.
- There have been strong pleas that the journal be brought out on a more regular basis. To date, issues have been held back until a fairly sizeable number of articles are available for publication. This has resulted in two to

three issues per year. In future we intend bringing out four issues, two of which will be regular issues, and the other two will be special issues dealing with some topical theme. This process has already started in that the next issue (in October) will be on IT and Development. A further special issue on Networking/Telecommunications is planned for mid-1996. Articles for the former special issue are currently being reviewed. Potential contributors to the latter special issue might want to start thinking about possible publications, but should delay submission of manuscripts until further details are provided in a formal call for papers.

- To date, SACJ has not obliged contributors to sign away copyright. Although the matter of copyright has become somewhat obscured in the age of electronic documents, the Internet, WWW, etc., SACJ will in future require that contributors sign a copyright form before their work is published. In dealing with issues relating to electronically available material, we shall follow guidelines proposed in recent issues of the Communications of the ACM.
- Some readers may have noticed that SACJ now appears on the World-Wide Web. This is due to the efforts of the production editor. The WWW home page address is provided on the front inside cover of the journal. Extensive information to potential subscribers and contributors has been provided. This includes information on submission procedures, document preparation, etc.

Abstracts of published articles are also given.

- Presently SACJ is sent to Inspec where selected articles are indexed. Arrangements are currently being made for Science Citation Index to provide a similar service. This should significantly increase exposure of SACJ's contents to international researchers.
- SACJ encourages contributions from young and/or inexperienced researchers and will assist them in various ways to attain the quality required by the journal. For example, they may be provided with additional editorial assistance (perhaps to be paid for, if warranted by the scope of the assistance). Referees will be urged to be encouraging in their feedback and to formulate feedback clearly and specifically in ways that will facilitate the revision process. Potential contributors may also request to be put in touch with a mentor to advise in planning and writing up research. As a further encouragement to young researchers, consideration is being given to an annual citation for the best student contribution.

Derrick Kourie and Lucas Introna
Editors

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The Recall Performance of Multiple Associative Memories – a Comparison of Thresholding Strategies

Anwar Vahed

Department of Computer Science, University of the Western Cape, Bellville, 7535

email: avahed@cscience1.uwc.ac.za

Abstract

The associative network presents a practical and efficient means for the storage and retrieval of data. Although the recall abilities of single-layer associative memories have been well researched [3], little investigation of a similar nature has been done on multi-layer associative memories. An earlier theoretical analysis of recall abilities of single-layer associative networks is extended here to provide a more accurate formulation of empirical results and simulation results are presented in support of this analysis. The recall performance of the advanced distributed associative memory (ADAM) is shown to deliver significantly better recall performance than multi-layer associative memories using Willshaw thresholding at all layers. Intermediate layer parameters that would yield optimum recall performance are investigated and shown to compare favourably with values suggested by information-theoretic derivations.

Keywords: Associative memory, recall performance, neural networks.

Computing Review Categories: B.3.2, I.5.1

1 Introduction

The associative network model loosely defines a general category of neural network that have been specialised into various types. These networks differ essentially in the way their connection weights are determined, the numeric nature of the weights, and the recall procedure they employ. Variations of associative memories have been applied in many areas of research; it has been used to represent neurophysiologically plausible theories of structures of the brain [3] and has provided a model for the practical realization of data association in scientific and engineering applications. For example, associative memories have been applied in the recognition and reconstruction of images [1], the categorization of data [5] and in the retrieval of information from partial references [4].

The associative net as presented here employs no feedback mechanism and all patterns and weights are unipolar binary. Although the storage efficiency of such single-layer memories have been extensively researched [7, 8], little investigation of a similar nature have been done on multi-layer architectures. The results reported here are essentially threefold:

- The initial analysis of the recall characteristics of the associative memory by Willshaw [7] is briefly reviewed. This analysis is extended here and is shown to be a more accurate formulation of empirical results.
- Results of investigations of the recall performance of multilayer memories using thresholding techniques of Willshaw and Austin [2] (ADAM) are presented and analysed.
- Thirdly, simulation results of intermediate pattern parameter values sought for optimal recall performance are compared with values obtained from an information-theoretic analysis.

2 Associative Memory Architecture

The task of the associative memory considered here is to store a set of R pattern pairs $\mathcal{S} = \{(\xi^{(\mu)}, \zeta^{(\mu)}) \mid \mu = 1, 2, \dots, R\}$ where $\xi^{(\mu)} = [\xi_1, \xi_2, \dots, \xi_n]^t$ and $\zeta^{(\mu)} = [\zeta_1, \zeta_2, \dots, \zeta_m]^t$. (The superscript t denotes the transpose.) Upon presentation of a possibly degraded pattern $\mathbf{x}^{(k)}$, the network is to produce a recalled pattern $\mathbf{y}^{(k)}$, such that $\mathbf{y}^{(k)} \in \mathcal{S}$ and its associated input pattern $\xi^{(k)}$, most closely resembles $\mathbf{x}^{(k)}$. The values in each pattern are denoted as ON (1) or OFF (0) bits.

For a given pattern set a fixed number of elements are randomly set ON in all input patterns. The same applies to the output patterns, though this number may differ from that of the input patterns. The association between the pattern pairs in \mathcal{S} is established by setting each weight w_{ij} ON if the input pattern component ζ_i and output pattern component ξ_j are simultaneously ON for all components and all training instances. Otherwise a weight remains OFF. More succinctly,

$$w_{ij} = \bigcup_{\mu=1}^R \zeta_i^{(\mu)} \cdot \xi_j^{(\mu)} \quad (1)$$

where $\bigcup_{\mu=1}^R x_\mu$ is the disjunction of all events x_μ for $\mu = 1, 2, \dots, R$. Figure 1 shows the weight matrix of an associative memory characterized by equation 1. Modified weights are indicated by shaded circles.

For some test input pattern \mathbf{x} (hereafter called a *cue*), the *response* of the i -th output component r_i , of the network is defined to be the sum of all conjoint activities between the cue component and weight matrix. That is, $r_i = \sum_{j=1}^n w_{ij} x_j$.

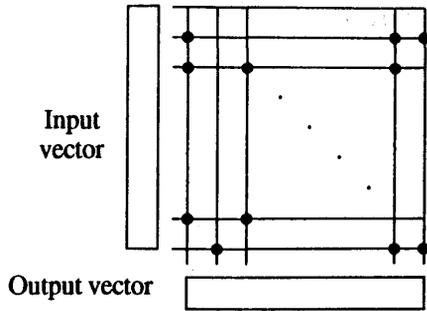


Figure 1. Representation of the weight matrix W . Shaded circles represent ON weights.

3 Thresholding Techniques

The manner in which the network output is determined from its response is a crucial influence on the recall efficiency of the memory. Some thresholding techniques are briefly reviewed below.

Willshaw's Thresholding

The recall procedure introduced by Willshaw [8] sets the threshold T at a level equal to or greater than the number of ON elements in the input pattern. More formally, $T = \sum_{i=1}^n x_i^{(\mu)}$ and the output y_i , is defined by the function

$$y_i = \begin{cases} 1 & \text{if } r_i \geq T \\ 0 & \text{otherwise} \end{cases}$$

n-Point Thresholding

The advanced distributed associative memory (ADAM) introduced by Austin [2] consists of two layers. The first layer is thresholded by selecting the n highest values in the network response where n is the number of ON elements in the stored output patterns. This technique is known as *n-point thresholding*.

The second layer takes the thresholded output of the first and performs Willshaw's thresholding on it to give the final output. The first layer associates patterns with predetermined class patterns each of which characterizes a particular output class on which the net is to be trained. This thus effectively functions as a feature classifier or *n-winner-take-all* network. The number of ON elements in the training patterns are assumed to be constant in both *n-point*- and Willshaw's thresholding. The principal difference is that with *n-point* thresholding, the output is determined from knowledge of the stored output pattern whereas the input pattern provides that information in case of Willshaw's thresholding. The latter is clearly a more intuitive notion.

4 Analysis of Recall Performance

The recall performance of single-layer associative networks have been analysed extensively [7]. It has been shown that for a given recall performance criterion and net parameters there exist a definite upper bound to the number

of patterns than can be stored reliably. We briefly review the earlier analysis of recall performance here.

Initial analysis

Consider an associative network storing unipolar binary weights as described previously. The input patterns are n_i -dimensional with a fixed number m_i of randomly distributed ON elements. Similarly, the output patterns are n_o -dimensional containing precisely m_o randomly distributed ON elements. The probability that a given input element is ON is $\alpha_i = m_i/n_i$ and likewise for the output pattern, $\alpha_o = m_o/n_o$. The probability of a particular weight being modified after R associations can be shown to be

$$\begin{aligned} \hat{\rho} &= 1 - (1 - \alpha_i \alpha_o)^R \\ &\simeq 1 - \exp(-R \alpha_i \alpha_o) \end{aligned} \quad (2)$$

Let the criterion for acceptable recall be that at most one output is spuriously ON. Usually, $m_o \ll n_o$, so this requirement can be approximated by

$$n_o \hat{\rho}^{m_i} \leq 1 \quad (3)$$

The number of patterns R that can be stored such that at most one unit is spuriously ON during recall is thus from equation (2),

$$R \simeq -\frac{1}{\alpha_i \alpha_o} \ln(1 - \hat{\rho}) \quad (4)$$

The responses on $n_o - m_o$ output elements that are supposed to be OFF, are distributed according to the binomial $b(m_i, \hat{\rho})$. The probability that the response on any of these elements is m_i , is therefore $b(r = m_i; m_i, \hat{\rho}) = \hat{\rho}^{m_i}$

Extended analysis

Recent studies [3] revealed some discrepancy between the results predicted by the initial analysis and that obtained by simulation. Although the position of the ON elements are randomly selected, it does not imply that each element position in the pattern set will be ON a proportion m_i/n_i times. The distribution of the binomial $b(m_i, \hat{\rho})$ hence does not hold for all units.

Let the *unit usage* u_i of bit position i be the number of times that that unit is ON for all patterns in a given set. That is, $u_i = \sum_{\mu=1}^R x_i^{(\mu)}$. The unit usage is distributed binomially with probability α_o . Figure 2 shows u_i for 1024 patterns each of dimension 1024 and containing 32 randomly generated ON elements. (Henceforth, the set of r patterns each of dimension n and containing m randomly generated ON patterns will be denoted by $RrNmM$.) As predicted, the distribution is approximately according to the binomial $b(1024, 0.032)$.

For R training instances and $k \leq R$, the probability that a given output unit has a unit usage $u = k$ is

$$P(u = k) = b(k; R, \alpha_o) = \binom{R}{k} \alpha_o^k (1 - \alpha_o)^{R-k}$$

The probability that a weight has been modified during the

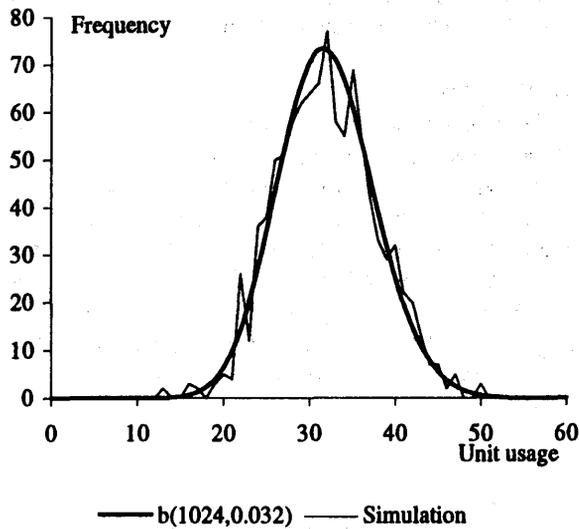


Figure 2. The unit usage u_i , for an R1024N1024M32 pattern set. The solid line is the binomial $b(1024, 0.031)$.

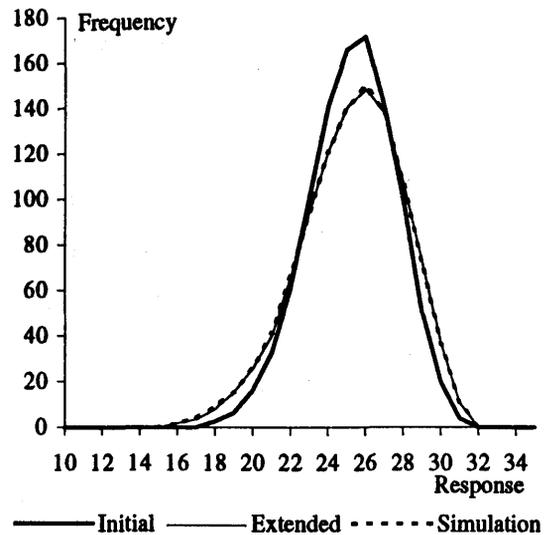


Figure 3. Distribution of erroneously ON responses for R1600N1024M32 patterns.

storage of k associations is $\rho[k] = 1 - (1 - \alpha_i)^k$. So, given a unit usage k for some output unit, the probability that the response r , of that unit is x is

$$P(r = x | u = k) = \binom{m_i}{x} (\rho[k])^x (1 - \rho[k])^{m_i - x}$$

The probability $P(r = x)$ where $x > 0$, is given by

$$P(r = x) = \sum_{k=0}^R X_k Y_k$$

where,

$$X_k = \binom{R}{k} \alpha_o^k (1 - \alpha_o)^{R-k}$$

and

$$Y_k = \binom{m_i}{x} (\rho[k])^x (1 - \rho[k])^{m_i - x}$$

Figure 3 is an example of distributions predicted by the initial and extended analysis, and how they compare with simulation results. The pattern set parameters are $R = 1600$, $n_i = n_o = 1024$ and $m_i = m_o = 32$. As shown, the values obtained from the extended analysis coincide almost exactly with that of the simulations. Simulation results were averaged over least five different pattern sets. The standard deviation was very small and hence these results are quite repeatable. For all results, the recall characteristics of single-layer networks coincided well with values predicted by the extended analysis.

Table 1. Network parameters used to compare the recall performance of ADAM and DWIL networks.

Input		Intermediate		Output	
n	m	n	m	n	m
1024	32	1024	32	1024	32
2048	64	1024	32	2048	64
4096	128	1024	32	4096	128

5 Recall Performance with Full Cues

The general approach in these investigations was to consider the mean output error expressed in terms of the Hamming distance between recalled and target patterns. Table 1 gives some of the network parameters used to explore the recall performance of the ADAM network and the two layer network using Willshaw's thresholding at both layers (hereafter, the DWIL network).

The mean output error for the ADAM and DWIL networks trained with the pattern sets in Figure 1 is shown in Figure 4. Predictably, the recall performance deteriorated as the networks saturated with stored patterns. Generally, the ADAM net was more storage efficient than the DWIL network, but this advantage diminished as the size of the pattern dimension increased. As shown, with 1024-dimensional input and output patterns, the performance of the ADAM network was almost as good as the DWIL network with twice this dimensionality.

Interestingly, the recall performance of the storage equivalent single layer network using Willshaw's thresholding turned out to be better than both multi-layer architectures. (A single layer network is considered to be storage equivalent to a multilayer one if they have the same number of weights.) There is overall, a negative trade-off between the recall efficiency and the gain in storage requirements promised by multi-layer architectures.

If the same intermediate pattern is recalled, the re-

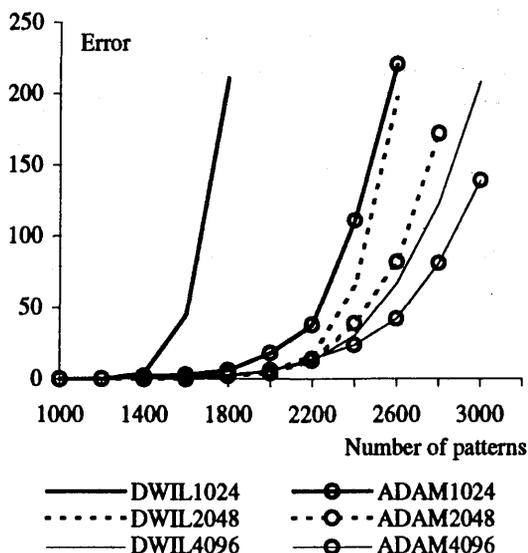


Figure 4. Mean output error for the ADAM and DWIL network for pattern dimensions as given in Figure 6.

call performance is the same for both networks since the same thresholding technique is applied in the second layer. Rather, the difference can be ascribed to the nature of the error at the intermediate layer. That is, whether the errors are due to spurious or missing elements.

For n-point thresholding, if one output is incorrectly thresholded ON, there will be precisely one other output unit that will also be incorrectly thresholded OFF. This means that the ADAM network would always exhibit output errors of Hamming distances that are multiples of 2 from the target.

6 Partial and Noisy Cues

Partial Cues

Simulations with partial cues were conducted using pattern sets with various combinations of ON bit densities and dimensions. Training set sizes ranged from 200 to 2400. Partial cues were generated by turning randomly selected ON bits OFF in all of the original pattern sets. This number of bits in the input pattern were progressively reduced from 50 to 4.

Figure 5 shows an example for $R = 1000$. Here, the DWIL network started to deteriorate when the cues contained 14 (out of the original 50) ON bits and 22 for the ADAM network. In contrast to full cues, the DWIL recall performance was generally somewhat better than the ADAM network.

Noisy Cues

When full or noisy cues are presented to a trained network employing Willshaw's thresholding it is not possible to produce errors of a partial nature since the weights connecting all ON input units impinging on a given unit that should be ON will have been modified during training. Thus, any

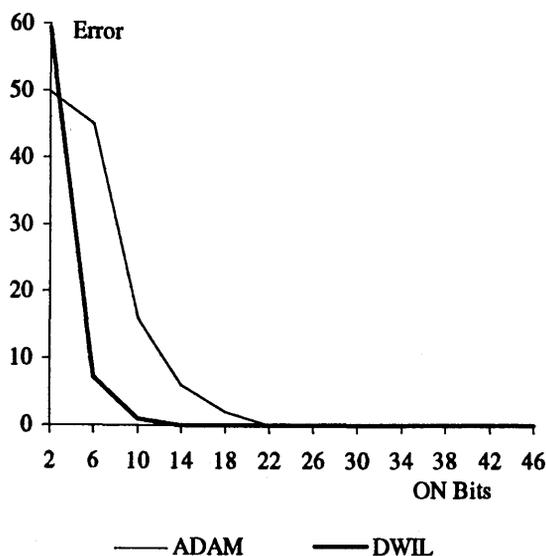


Figure 5. Mean output error for partial cues. Pattern parameters were R1000N2048M50 for input and output and R1000N512M9 for the intermediate layer.

output error at the intermediate layer will always be of a spurious nature. This is not necessarily so for the ADAM network.

For noisy cues, there is a catastrophic degradation in the performance of the DWIL network and the ADAM network results were markedly better. The intermediate pattern obtained through n-point thresholding is thus more suitable as input to the second layer. Figure 6 shows the recall performance for networks with R1600N2048M32 parameters for the input and output layer, and R1600N512M9 for the intermediate layer. The number of spurious bits were progressively increased from 1 to 32. The performance of the DWIL network improves substantially if the threshold at the intermediate layer is changed to m_i instead of the number of ON bits in the cue. The graph indicated by DWIL@Mi in Figure 6 illustrates that although much better, the DWIL network's performance is still not as good as the ADAM network.

7 The Intermediate Layer

Assume that all intermediate patterns are perfectly recalled. The performance of the network thus depends only on the second layer. From equation 3 the expected number of incorrectly ON elements in the output pattern is approximately

$$E = n_o \hat{\rho}_h^{m_h} \tag{5}$$

where $\hat{\rho}_h$ is the density of the ON elements in the intermediate layer. The change of E with respect to the number of ON elements in the output layer is

$$\frac{dE}{dm_h} = E \left(\ln \hat{\rho}_h + \frac{m_h}{\hat{\rho}_h} \frac{d\hat{\rho}_h}{dm_h} \right) \tag{6}$$

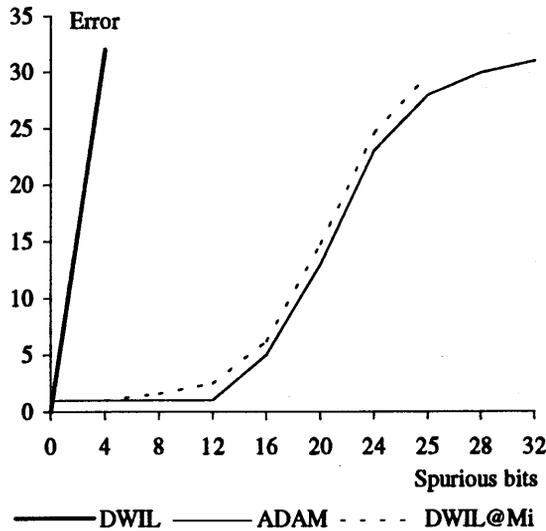


Figure 6. Mean output error for noisy cues. Input and output pattern parameters are R1000N2048M32 and R1000N512N9 for the intermediate layer.

and by equation 4,

$$\frac{dE}{dm_h} \simeq E (\hat{\rho} \ln \hat{\rho} - (1 - \hat{\rho}) \ln(1 - \hat{\rho}))$$

This equation is minimized if $\hat{\rho} = \frac{1}{2}$. Thus, storage will be optimized when

$$m_h \simeq 0.69 \frac{n_h n_o}{R m_o} \quad (7)$$

Preliminary studies indicate that networks that are trained with patterns of such densities yield better recall performance than similarly configured Hopfield and Bidirectional associative Memories.

Intermediate Layer Density

The analysis of the recall capabilities of associative memories from an information theoretic perspective [7, 8] posited amongst others, a functional relationship among network parameters that would yield optimal information representation in a single layer network. To analyse this relationship, input and output pattern parameters were kept constant (at $n = 2048$ and $m = 64$) while the intermediate pattern dimension was varied between 512 and 2048. The density of ON bits was chosen to range between 16 and 64. As expected, the mean output error decreased as the intermediate pattern dimension increased relative to the other dimensions.

It turns out that the recall performance of a two layer network is particularly sensitive to the density of the ON bits and the ratio of the intermediate pattern dimension relative to the other dimensions. Simulations with $\alpha = 0.03125$ for the input and output layers, and $\alpha_h = 0.03125$ and 0.06125 showed a marked improvement in the recall performance for the smaller value of α_h . This suggested

as supported by the theory, that there exists an optimal value for α_h since it cannot be zero. Simulation results for network parameters RrN2048M64 for the input and output layers and $n = 224$ for the intermediate layer are shown in Figure 7. All patterns were correctly recalled for both the ADAM and DWIL networks. The value computed from section 7 is approximately 6.9 for $R = 800$ and 12.2 for $R = 400$. As shown, there is a fair correspondence between these values and empirical results. Similar results were also obtained for other parameter values.

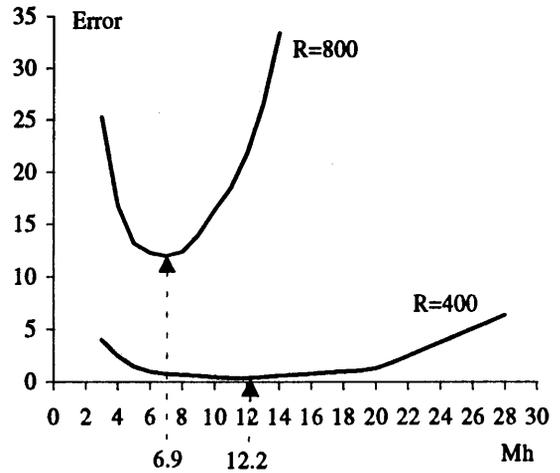


Figure 7. Mean output error versus m_h . Input and output pattern parameters are RrN2048M64 and RrN224Mm for the intermediate layer.

8 An Information Theoretic Approach

It has been shown from information theoretic principles [6] that a single layer network input pattern with a low density of ON elements relative to the number of output elements is more storage efficient. This argument is extended here to a double layer network.

Suppose that intermediate patterns are perfectly recalled. The information required to represent one target pattern in the second layer is $\log_2 \left(\frac{n_o}{m_o} \right)$ bits. After the network has been trained with R patterns, the information stored would be

$$I = R \log_2 \left(\frac{n_o}{m_o} \right) \text{ bits.}$$

The total number of bits available for storage in the entire network is $n_h(n_i + n_o)$. Let the *information efficiency* be

$$\eta = \frac{I}{n_h(n_i + n_o)}$$

By Stirling's formula, $\log_2 \left(\frac{n}{m} \right) \simeq m \log_2 n$ for

$m/n \ll 1$. Thus,

$$\eta = \frac{Rm_o \log_2 n_o}{n_h(n_i + n_o)}$$

Let $\hat{\rho}_1$ and $\hat{\rho}_2$ be the expected density of the modified weights in the first and second layer respectively. Using equation 4 applied to the second layer,

$$\eta \simeq -\frac{n_o}{n_i + n_o} \ln(1 - \hat{\rho}_2) \ln \hat{\rho}_2 \ln 2$$

This expression is maximized when $\hat{\rho}_2 = 0.5$ and so,

$$m_h = \frac{n_h n_o \ln 2}{Rm_o}$$

Since the same number of patterns stored in the first and second layer, for the optimal value for $\hat{\rho}_2$ it holds from equation 4 that

$$\frac{1}{\alpha_i} \log_2(1 - \hat{\rho}_1) = -\frac{1}{\alpha_o}$$

and hence,

$$\hat{\rho}_1 = 1 - 2^{-\alpha_i/\alpha_o}$$

For input and output patterns of the same dimension, $\hat{\rho} = 0.5$. So, $n_h = 2^{m_i}$. In general thus,

$$n_h = (2^{-\alpha_i/\alpha_o} - 1)^{m_i}$$

The value of n_h scales up exponentially with m_i and it should be that $\alpha_i \gg \alpha_o$ for m_o to have any sensible value. The intermediate layer thus have to be sparsely loaded to obtain a reasonable recall error.

9 Conclusions

A number of results emerged from these investigations. Values obtained from the extended theory were substantially more accurate predictors of simulation results. With the exception of partial cues, the ADAM network produces markedly better recall performance than the DWIL network. This is particularly so for noisy input. However, this advantage diminishes as storage requirements approached that of equivalent single layer memories – even for mean errors greater than one.

The recall performance of multi-layered networks is no better than single-layer ones with similar storage requirements. Moreover, performance deteriorates rapidly when additional intermediate layers are introduced. Preliminary results from experiments with partially and particularly sparsely connected networks of this type, seem to hold more promise.

The intermediate layer density was found to be a crucial determinant of recall performance. Values obtained from simulations indicated that the dimension of the intermediate pattern is exponentially related to the density of the ON bits therein. This accorded reasonably well with results

obtained from information theoretic considerations.

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