Two experimental studies on creative concept combinations in modular design of electronic embedded systems

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This paper discusses the nature of concept combinations in modular design of electronic embedded systems as well as the relation between combination characteristics and novelty, quality, and usefulness of the produced solutions. Through two experimental studies, this work explored the frequency of relation-based and property-based combinations in embedded design solutions, and how the specifics of the given building blocks, i.e. salience, relatedness and number, influenced the produced combinations. The impact of popular aids, like titles and short descriptions (briefs), in improving novelty, quality, and usefulness of the designs was also analyzed. Design solutions include mostly relation-based combinations. Design novelty correlates mainly to the purpose and context of the produced combinations. Novelty is aided by titles but not by briefs.

Keywords: creativity, design cognition, system design, concept combinations

Design methodologies for electronic embedded systems stress the importance of modularity. Modular design solutions are created by connecting basic building blocks with well defined functionality, interfaces, and performance, e.g., components, library circuits, or intellectual property (IP) blocks. Modular design reduces design cost and effort by reusing building blocks, and enhances design correctness as repeated testing and verification of blocks eliminate most of their errors (Conradi, 1999; Kaeslin, 2008). New blocks are rarely created. Thus, designing original electronic embedded systems mainly involves finding new ways to relate blocks. This explains the significance of finding novel and useful combinations among building blocks.

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The importance of concept combinations in creativity has been intensely studied by research in cognitive psychology (Estes & Ward, 2002; Simonton, 2010; Smith, Osherson, Rips, & Keane, 1988). Concept combinations are of three kinds. *Property-based combinations* transfer features from one concept, called

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modifier, to another concept, called head concept (Wisniewski, 1996). For example, Lagne (2000) explains that in ‘zebra clam’, property ‘stripes’ of the modifier concept ‘zebra’ is transferred to the head concept ‘clam’. *Relation-based combinations* introduce new relations between concepts (Lagne, 2000; Wisniewski & Love, 1998). For instance, ‘mountain stream’ is a relation-based combination that defines a location-based connection between concepts ‘mountain’ and ‘stream’ (Lagne, 2000). *Hybrid combinations* are a mixture of relation and property-based combinations, such as combination ‘musician painter’ (Wisniewski, 1997). Various conditions influence the kind of produced combinations, like the salience of concept features (Hampton, 1996), and the similarity and abstraction level of combined concepts. More similar concepts originate more property-based combinations, while dissimilar, yet easy- to-relate concepts create more relation-based combinations (Wisniewski, 1997). Abstract concepts favor relation-based combinations, and basic concepts help property-based combinations (Markman & Wisniewski, 1997). Property-based combinations are harder to create (Lagne, 2000) but enable new features beyond those of the initial concepts (Wisniewski, 1997), even though other studies challenge these findings (Wilkenfield & Ward, 2001; Wisniewski & Love, 1998). Creativity is higher for concepts with less typical, less salient features (Hampton, 1987), combinations of dissimilar features (Hastie, Schroeder, & Weber, 1990; Markman & Wisniewski, 1997), abstract concept combinations (Ward, Patterson, & Sifonis, 2004), and anomalous combinations (Baughman & Mumford, 1995; Wilkenfield & Ward, 2001).

Enhancing creativity in electronic embedded system design based on the insight gained from studies in cognitive psychology is not straightforward. Studies in psychology rarely capture the specificity and complexity of embedded system design problems. Problems in embedded system design are often wicked (ill-defined). Wicked problems express loosely or incompletely specified requirements, or present needs based on organizational or personal perspectives, judgments, predictions, or beliefs (Coyne, 2005; Darlington & Culley, 2004). Modularity is intrinsic to the design process (Dahmus, Gonzalez-Zugasti, & Otto, 2001; Poole & Simon, 1997; de Vries & Achten, 2002) while in other domains, like architecture or mechanical engineering, modularity is less common or identifying modules is a step that follows design and implementation (Stone, Wood, & Crawford, 2000). Also, embedded systems are programmable, which enhances their capability to be customized to specific needs (Doboli & Currie, 2010). Thus, designs can achieve higher utility (Poole & Simon, 1997). Finally, electronic systems are more complex than other engineering systems, e.g., in mechanical engineering, therefore conceptualization is harder (Darlington & Culley, 2004). However, the complexity of electronic systems can be effectively tackled through top-down design methodologies, in which design activities are performed separately at consecutive levels of abstraction, including behavioral level, logic level (e.g., gate netlist, schematic), and physical level (i.e. layout) (Doboli, Dhanwada, Nunez-Aldana, & Vemuri, 2004; Doboli & Vemuri, 1998; Wang,