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PREFACE

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This special volume of Theory and Applications of Categories (TAC) addresses the theme "Chu Spaces: Theory and Applications." The idea for the volume grew out of the workshop of that name organized by the volume's editors in association with the conference Logic in Computer Science (LiCS'2000) held at Santa Barbara in 2000. We conceived the scope of the volume as not being limited to the material presented at the workshop itself but extending beyond it to embrace a wider range of topics related to Chu spaces and Dialectica constructions.

By way of complement to Barr's article in this issue on the conceptual evolution of Chu spaces we offer here some prefatory remarks of our own on the nature, uses, and history of Chu spaces. We then give our perspective on where this volume's papers fit in the overall scheme of things. Further material on Chu spaces can be found at the website `http://chu.stanford.edu` maintained by the second editor.

1. Framework

A Chu space over an object k is a triple (a, r, x) consisting of two objects a and x that transform respectively forwards and backwards, along with a morphism $r : a \otimes x \to k$ that can be viewed as a k-valued relation between a and x. In the ordinary case, a, x, and k are sets A, X, and K, and r is a function $r : A \times X \to K$ that, when $K = \{0, 1\}$, reduces to the usual notion of an ordinary binary relation between two sets. Thinking of the elements of A as the points of the space, the elements of X may be understood as dual points, states of an automaton, or places of a Petri net depending on the application. More generally the objects and morphisms are drawn from an autonomous (symmetric monoidal closed) category V with tensor product $a \otimes b$, tensor unit I, and internal hom $a \multimap b$.

The notion of direction of transformation of a and x is made precise by defining a morphism $(a, r, x) \to (a', r', x')$ of Chu spaces to be a pair (f, g) of morphisms $f : a \to a'$, $g : x' \to x$. These are required to satisfy an *adjointness condition*, which in the ordinary case where the set A has elements $\alpha, \ldots$ and X' has elements $\xi, \ldots$, is expressible as $r'(f(\alpha), \xi) = r(\alpha, g(\xi))$ for all $\alpha \in A$ and $\xi \in X'$. Morphisms compose via $(f', g')(f, g) = (f'f, gg')$, whose associativity is straightforward to verify. When $V = \mathsf{Set}$ the resulting ordinary category of ordinary Chu spaces over K and their morphisms is denoted $\mathsf{Chu}(\mathsf{Set}, K)$; for other V a further step enriches the homsets to make them objects

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of V and $\mathsf{Chu}(V,k)$ a V-category [Kel82].

The autonomous structure of V is inherited by $\mathsf{Chu}(V,k)$, along with a contravariant involution $(a,r,x)^* = (x,r',a)$ where $r'(z,a) = r(a,z)$. This involution makes the latter category $*$-autonomous in Barr's terminology. V embeds as a submonoidal (but not subautonomous) category of $\mathsf{Chu}(V,k)$ via $a \mapsto (a, \varepsilon_{ak}, a \multimap k)$ where $\varepsilon_{ak} : a \otimes (a \multimap k) \to k$ is evaluation; that is, $T(a \otimes b) \cong T(a) \otimes T(b)$ but only $T(a \multimap b) \to T(a) \multimap T(b)$ (namely transpose of evaluation), where $T : V \to \mathsf{Chu}(V,k)$ is the embedding in question.

$\mathsf{Chu}(V,k)$ inherits the colimits and limits of V in matched pairs. That is, if V has both J-limits and J-colimits for a given small category J constituting the shape of the relevant diagrams, then so does $\mathsf{Chu}(V,k)$. In particular if V has finite sums and products then so does $\mathsf{Chu}(V,k)$, relevant to the application to linear logic.

2. History and Applications

As Michael Barr explains in his contribution to this volume and in [Barr96], his original application for the Chu construction given in his book [Barr79] was to have many more $*$-autonomous categories than the half dozen he had observed in nature. The Chu construction produces a $*$-autonomous category for every autonomous category (V,k), thinking of k as a distinguished object or point.

At the Conference on Categories in Computer Science and Logic held in Boulder in 1987 it was realized that several people had more or less simultaneously arrived at the view of linear logic, specifically its multiplicative fragment MLL, as the internal logic of a $*$-autonomous category. Barr, Robert Seely, Martin Hyland, and Valeria de Paiva all spoke on modeling linear logic using $*$-autonomous categories, with additional structure for the exponentials. Seely's and de Paiva's articles appeared in the proceedings of the conference [See89, dP89a].

In her 1988 Cambridge thesis advised by Martin Hyland, de Paiva modeled Gödel's Dialectica interpretation in terms of a category denoted DC, reminiscent of the Chu construction. Subsequently, following a suggestion of Jean-Yves Girard, she proposed a variant of DC, called GC closer to the Chu construction. Both constructions provide models of Linear Logic, including the exponentials. Both constructions differ from Chu's construction in that the morphism adjointness condition is taken as an inequality instead of an equality: the inequality is read as logical implication, instead of logical equivalence.

In 1990 Carolyn Brown and Doug Gurr [BG90] applied de Paiva's Chu-like Dialectica Category GC to the semantics of Petri nets, identifying the two sets of respectively transitions and places of a Petri net as an object of GC. In 1991 Brown, Gurr and de Paiva [BGdP91] formulated GC as GNet, having as objects Petri nets and as morphisms simulations of one Petri net by another. Existence of a morphism between two Petri nets was a sufficient condition for the correct simulation of one by the other. They illustrated this for the problem of verifying correctness of an error-correcting message handler given a simpler non-error-correcting one defining the desired behavior on error-free messages, accomplished by exhibiting a morphism between them.

Yves Lafont and Thomas Streicher proposed the name $\mathbf{GAME}_K$ for the case $\mathsf{Chu}(\mathsf{Set}, K)$ of the Chu construction [LS91]. This was the first paper to relate linear logic and games, a connection that Blass, Abramsky and others subsequently developed into several applications of linear logic ideas to programming language semantics. They also pointed out the concrete embedding, or **realization** in the sense of Pultr and Trnkova [PT80], of the categories of topological spaces, Girard's coherent spaces, and vector spaces over an arbitrary field k, into $\mathsf{Chu}(\mathsf{Set}, K)$ for suitable sets K in each case.

In 1992 Vineet Gupta and Vaughan Pratt embedded the pomset model of concurrent processes in $\mathsf{Chu}(\mathsf{Set}, 2)$ by interpreting events as the points, and configurations of events as the states or dual points, of a Chu space. They showed that this representation mapped the concurrency operations of orthocurrence and concurrence to respectively tensor product and sum (coproduct) [GP93]. This work became the basis for Gupta's thesis "Chu Spaces: A Model of Concurrency" [Gup94].

Dusko Pavlović [Pav93, Pav97] exhibited an adjunction between the 2-categories of pointed autonomous categories and $*$-autonomous categories, and showed that its right adjoint 2-functor was the ordinary (unenriched) Chu construction $\mathsf{Chu}_O(V, k)$. Pavlović suggested a way of extending it to produce V-categories, though necessarily not as part of any adjunction of this kind since V is variable.

At MFCS'93 [Pra93] Pratt extended the concrete universality results of Lafont and Streicher to all algebraic and relational structures of total arity n, which he realized as Chu spaces over 2^n; for example the category Grp of all groups, understood as ternary relational structures, embeds concretely in $\mathsf{Chu}(\mathsf{Set}, 8)$. At LICS'95, with this universality of Chu spaces in mind, Pratt proposed [Pra95b] a two-dimensional coordinatization of the universe of all algebraic and relational structures: discrete to coherent depending on the aspect ratio of the Chu matrix, and simple to complex depending on the cardinality of the dualizing set K. At Linear Logic'96 in Tokyo Pratt presented a related universality result, that every small category C embeds in $\mathsf{Chu}(\mathsf{Set}, |C|)$ and moreover concretely when C is concrete [Pra96].

At TAPSOFT'95 Pratt proposed Chu spaces as a solution to René Descartes' problem of how body and mind could interact by interpreting the points of a Chu space as body, its dual points as mind, and its matrix as the mechanism of their interaction [Pra95a] (a topic perhaps more appropriate for philosophers than programmers).

In 1997 Jon Barwise and Jerry Seligman produced their book "Information Flow: The Logic of Distributed Systems" [BS97], yet another independent rediscovery of Chu spaces. Using the paradigm of infomorphisms as information flow along information channels, with points and states designated as tokens and types, they consider the application of infomorphisms to distributed systems, Boolean inference in state spaces, reasoning at a distance, speech acts, vagueness, representational systems, and quantum logic.

At a Stanford seminar in 1998 Johan van Benthem defined a notion of flow formula as one that universally quantifies the points and existentially quantifies the states of a Chu space, and showed that the flow formulas were, up to equivalence, exactly those first order formulas preserved by Chu transforms [vBen00]. Sol Feferman applied a manysorted interpolation theorem he had proved in 1968 to strengthen and generalize this result [F03].

In a talk at CT'97 Pratt asked whether every dinatural transformation between MLL functors in $\mathsf{Chu}(\mathsf{Set}, K)$ interpreted some MLL proof net, subsequently answered in [Pra03] in the negative with a dinatural endomorphism of $A \multimap A$. At LICS'99 Harish Devarajan, Dominic Hughes, Gordon Plotkin and Pratt [DHPP99] gave a positive answer to the same question with dinaturality strengthened to binary logicality. Attempts to extend this result to MALL in 2000 ran up against the lack of a satisfactory definition of MALL proof net; Hughes then focused exclusively on this problem, joined near the end by Rob van Glabbeek, resulting in a satisfactory definition presented at LICS'03 [HG03].

In 1999 Eva Schläpfer at McGill defined a group algebra for topological Hausdorff groups using the Chu construction [ES99], based on her Fribourg Ph.D. work under Heinrich Kleisli. Such algebras have traditionally been defined measure-theoretically, typically via the Haar measure; the benefit of the Chu approach is that it avoids measure theory altogether.

The Coimbra School on Category Theory and Applications included a course of six lectures by Pratt on Chu spaces [Pra99]. Material covered included special and general realizations, operations on Chu spaces, axiomatics of multiplicative linear logic (MLL), and full completeness of MLL for Chu spaces.

3. Contents

The papers in this issue by Barr, Cockett *et al*, Koslowski, and Pratt look backwards and inwards at historic and foundational aspects of Chu spaces. The papers by de Paiva, Ritter and de Paiva, and Shirahata treat aspects of the dialectica categories and applications to intuitionistic and classical logic. Zhang and Shen consider applications of Chu spaces to Formal Concept Analysis.

Barr gives a history of the Chu construction, as a mathematical concept originally intended simply to produce topological vector spaces. He traces the roots of the construction back to George Mackey's 1945 thesis. Finally he proposes an elegant construction of $\mathsf{Chu}(V, k)$ by first showing that $V \times V^{\mathrm{op}}$ is $*$-autonomous, thus giving $\mathsf{Chu}(V, 1)$, and then obtaining $\mathsf{Chu}(V, k)$ as the category of M-actions for the monoid object $M = (I, k)$ in $V \times V^{\mathrm{op}}$.

Cockett, Hasegawa, and Seely show that the double-negation axiom characterizing $*$-autonomous categories, normally required only to be an isomorphism, can be taken to be identity without significant loss of generality. This brings $*$-autonomous categories in line with both Chu spaces and linear logic in that regard, both of which take double-negation to be identity.

Koslowski proposes an alternative view of the Chu construction as a bicategorical construction in its own right. He begins by constructing a closed bicategory that is not $*$-autonomous, and then identifies within it a $*$-autonomous subcategory.

Pratt poses the question of whether the construction of $\mathsf{Chu}(V, k)$ can be viewed as a completion of k understood as a small V-category with k as its one nontrivial homset. He answers this in the affirmative for $V = \mathsf{Set}$ and explores how this might generalize.

Turning to dialectica categories, de Paiva compares Chu spaces with Dialectica spaces and proves that the latter can be constructed when the base category is simply symmetric monoidal closed, instead of cartesian closed. A survey of previous work on dialectica categories fills a long-standing gap.

Ritter and de Paiva formulate full intuitionistic linear logic, the logical system corresponding to dialectica spaces, as a strongly normalizing Natural Deduction system, following Parigot's suggestions for natural deduction for classical logic.

Shirahata proposes a version of Gödel's Dialectica interpretation of linear (actually affine) logic. This gives rise to the same categorical construction of de Paiva's doctoral work, the category GC, which one can easily extend to a model of first-order affine logic. More interestingly Shirahata then proves syntactically that combining Girard's ?!-translation and his own affine Dialectica translation is essentially equivalent to composing the double-negation interpretation with Gödel's original Dialectica.

Zhang and Shen explore relationships between Chu spaces and the Darmstadt school of Formal Concept Analysis, FCA. They introduce "approximable concepts" and show that they represent algebraic lattices similar to Scott spaces but for the inclusion of a top element.

While by no means exhausting the scope of extant material falling under the Chu space rubric, these papers offer an indication of some of their directions. The editors hope that researchers will be motivated to further our understanding of Chu spaces and to extend the variety of uses to which they can be put.

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