

# Pacific Journal of Mathematics

**FREE COMPLETE EXTENSIONS OF BOOLEAN ALGEBRAS**

GEORGE WESLEY DAY

## FREE COMPLETE EXTENSIONS OF BOOLEAN ALGEBRAS

GEORGE W. DAY

From considering questions about the existence of free  $\alpha$ -complete Boolean algebras and free complete Boolean algebras, one is led naturally to the following problem: Given a Boolean algebra  $B$ , is it possible to embed  $B$  as a subalgebra in a complete Boolean algebra  $B^*$  in such a way that homomorphisms of  $B$  into complete Boolean algebras can be extended to complete homomorphisms on  $B^*$ ? In general, the answer is "no"; this paper establishes that  $B$  can be so embedded if and only if every homomorphic image of  $B$  is atomic. Several other equivalent conditions on  $B$  are also developed.

To express these ideas more precisely, we say that the complete Boolean algebra  $B^*$  is a *free complete extension* of the Boolean  $B$  provided that there exist an isomorphism  $i$  of  $B$  into  $B^*$  such that

(i) if  $h$  is a homomorphism of  $B$  into a complete Boolean algebra  $C$ , then there is a complete homomorphism  $h^*$  of  $B^*$  into  $C$  such that  $h^* \circ i = h$ ;

(ii)  $B^*$  has no regular complete proper subalgebra which contains  $i[B]$  — that is,  $i[B]$  completely generates  $B^*$ . A Boolean algebra  $B$  is said to be *superatomic* if every homomorphic image of  $B$  is atomic (or, equivalently, if every subalgebra of  $B$  is atomic). Our principal result, then, is that a Boolean algebra  $B$  has a free complete extension if and only if  $B$  is superatomic.

The problem of determining which Boolean algebras have free complete extensions arose from a conjecture made by L. Rieger in [7]. This conjecture is, in effect, that no infinite free Boolean algebra has a free complete extension; this has been verified by H. Gaifman in [3] and, independently and by different methods, by A. Hales, in [4].

Rieger proved, on the other hand, that for any cardinal numbers  $\alpha$  and  $\beta$  there exists a unique free  $\alpha$ -complete Boolean algebra on  $\beta$  generators. This result can be expressed by the statement that the free Boolean algebra on  $\beta$  generators has a unique free  $\alpha$ -extension (a *free  $\alpha$ -extension* of a Boolean algebra is defined in the same manner as a free complete extension, with the concepts of completeness and complete homomorphism replaced by those of  $\alpha$ -completeness and

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$\alpha$ -homomorphism). F.M. Yaqub generalized this results in showing ([10], § 2) that every Boolean algebra has a unique free  $\alpha$ -extension.

In addition, Yaqub found that the free  $\alpha$ -extension of a Boolean algebra is  $\alpha$ -representable if and only if it is isomorphic to an  $\alpha$ -field of sets. He also proved that if  $\alpha \geq 2^{\aleph_0}$  and the free  $\alpha$ -extension of a Boolean algebra  $B$  is  $\alpha$ -representable, then  $B$  is superatomic. In § 4, we prove that the converse of the second of these results follows from the first, when the first is supplemented with our own results.

In § 2, we derive several characterizations of the superatomic Boolean algebras. In our third section it is shown that every superatomic Boolean algebra has a free complete extension. Then, using the result of Gaifman and Hales mentioned above, we show that every Boolean algebra having a free complete extension is superatomic.

Boolean concepts which are used without definition in this paper are defined in [2] and [8]. We denote the join and meet of two elements  $a$  and  $b$  of a Boolean algebra by  $a + b$  and  $ab$ , respectively; the complement of  $b$  will be denoted by  $\bar{b}$ ; the join and meet of a set  $S$  of elements of a Boolean algebra will be denoted by  $\Sigma S$  and  $\Pi S$ , when they exist. To simplify certain arguments, we have assumed that if  $S = \phi$ , then  $\Sigma S$  and  $\Pi S$  are the zero and unit, respectively, of the Boolean algebra in which the operations are performed.

**2. Superatomic Boolean algebras.** As defined by Yaqub in [10], a Boolean algebra  $B$  is superatomic if every subalgebra and every homomorphic image of  $B$  is atomic. This concept had been formulated previously in a somewhat more general context by Mostowski and Tarski, who, in [6], defined a hereditarily atomic Boolean ring as a Boolean ring each of whose homomorphic images is atomic; they observed that a Boolean ring  $R$  has this property if and only if every subring of  $R$  is atomic. In addition, Mayer and Pierce, in § 3 of [5], discussed Boolean algebras with scattered ordered bases (a totally ordered set, or chain, is *scattered* if it contains no subset which is order-isomorphic to the chain of rational numbers); it follows from their work that every such Boolean algebra is superatomic. However, there do exist superatomic Boolean algebras which are not of this form — a simple example is the Boolean algebra of finite and co-finite subsets of an uncountably infinite set, ordered by set inclusion.

**THEOREM.** *If  $B$  is a Boolean algebra, then the following are equivalent:*

- (i) *every homomorphic image of  $B$  is atomic;*
- (ii) *every subalgebra of  $B$  is atomic;*
- (iii) *the Stone space of  $B$  is clairsémé (has no nonempty dense-*

*in-itself set*);

(vi) *every chain of elements of  $B$  is scattered*;

(v) *there is a sublattice  $S$  of  $B$ , whose elements generate  $B$ , such that every chain of elements of  $S$  is scattered*;

(vi) *no subalgebra of  $B$  is an infinite free Boolean algebra*.

*Proof.* The equivalence of (i) and (ii) is proven in [6], Theorem 3.12. We could, in fact, include in our collection of equivalent statements,

(i') *no homomorphic image of  $B$  is atomless*; since it is easily shown that this is equivalent to (i).

It is well-known that in the natural duality between Boolean algebras and their Stone spaces, the homomorphic images and atoms of a Boolean algebra correspond to the closed subspaces and isolated points, respectively, of its Stone space. Thus, (iii) is equivalent to (i) (this was observed in [5]).

A Boolean algebra generated by a chain of elements which is order-isomorphic to the rationals is necessarily atomless, and, in fact, is isomorphic to the free Boolean algebra on  $\aleph_0$  generators (as is shown on page 54 of [2]). Thus, (ii) implies (iv), and (vi) implies (iv). Moreover, if  $B$  is a nonatomic Boolean algebra, then  $B$  has an atomless element  $b$ ; if  $a$  is any element of  $B$  such that  $a < b$ , then for some element  $c$  of  $B$ ,  $a < c < b$ . Every nonatomic Boolean algebra can thus be shown to have a chain of elements which is order isomorphic to the rationals; hence, (iv) implies both (ii) and (vi).

It is clear that (iv) implies (v). We shall conclude our proof by showing that (v) implies (i'). Let us assume that  $B$  is a Boolean algebra generated by a sublattice  $S$ . Suppose that  $h$  is a homomorphism of  $B$  onto the Boolean algebra  $B'$ . If  $a$  and  $b$  are elements of  $S$  such that  $a < b$  and  $h(\bar{a}b)$  is neither an atom nor the zero element of  $B'$ , then there are elements  $s$  and  $t$  of  $S$  such that  $s < t$ ,  $h(\bar{s}t)$  is not the zero of  $B'$ , and  $h(\bar{s}t) < h(\bar{a}b)$ . This implies that either

$$h(a) < h(a + bs) < h(b)$$

or  $h(a) < h(a + bt) < h(b)$ . In either case, we have found an element  $c$  of  $S$  such that  $a < c < b$  and neither  $h(\bar{a}c)$  nor  $h(\bar{c}b)$  is the zero of  $B'$ . Thus we may conclude that either  $B'$  has an atom or  $S$  has a chain of elements which is order-isomorphic to the rationals. Hence, if  $B$  is generated by a sublattice  $S$  such that every chain of elements of  $S$  is scattered, then no homomorphic image of  $B$  is atomless.

REMARK. The equivalence of conditions (i) and (iii) of the theorem indicates that every clairsémé compact Hausdorff space whose topology

has a base of open-and-closed sets is the Stone space of a superatomic Boolean algebra. We can, in fact, make a stronger statement. If a compact Hausdorff space is clairsémé, then it is clearly totally disconnected; that is, it has only one-point maximal connected components. It is shown in Chapter I of [1] that every locally compact totally disconnected space has a base of open-and-closed sets. Thus, every clairsémé compact Hausdorff space is the Stone space of some superatomic Boolean algebra. (The author is indebted to Prof. M. Henriksen of Purdue University for this argument.)

**3. Free complete extensions of Boolean algebras.** In this section, we show that a Boolean algebra has a free complete extension if and only if it is superatomic. Let us observe first that the definition of the free complete extension of a Boolean algebra implies that if a Boolean algebra has a free complete extension, then it is unique in the following sense: if  $B_1^*$  and  $B_2^*$  are free complete extensions of the Boolean algebra  $B$ , and  $i_1$  and  $i_2$  are the isomorphisms of the definition which carry  $B$  into  $B_1^*$  and  $B_2^*$  respectively, then there is an isomorphism  $i^*$  of  $B_1^*$  onto  $B_2^*$  such that  $i^* \circ i_1 = i_2$ .

**THEOREM.** *If  $B$  is a superatomic Boolean algebra, then the field of all subsets of the Stone space of  $B$  is a free complete extension of  $B$ , with respect to the natural isomorphism  $i$  of  $B$  onto the field of open-and-closed subsets of its Stone space.*

*Proof.* Suppose that  $B$  is superatomic and that  $X$  is the Stone space of  $B$ . Let  $B^*$  denote the field of all subsets of  $X$ . It is clear that  $i[B]$  completely generates  $B^*$ , since  $X$  is Hausdorff and its open-and-closed sets form a base for its topology. It remains to be proven that if  $h$  is a homomorphism of  $B$  into a complete Boolean algebra  $C$ , then there is a complete homomorphism  $h^*$  of  $B^*$  into  $C$  such that  $h^* \circ i = h$ .

Recall that for ordinal  $\beta$ , we define  $X^{(\beta)}$ , the  $\beta$ -th derivative of  $X$ , as follows:  $X^{(0)} = X$ ;  $X^{(\beta+1)}$  is the set of all limit points of  $X^{(\beta)}$ ; and if  $\beta$  is a limit ordinal, then  $X^{(\beta)} = \bigcap \{X^{(\alpha)} : \alpha < \beta\}$ . Since  $X$  is clairsémé, every point of  $X$  is an isolated point of some derivative of  $X$ ; moreover,  $X$  has empty derivatives.

If  $p \in X$  and  $p$  is an isolated point of  $X^{(\beta)}$ , let  $b_p$  be an element of  $B$  such that  $i(b_p) \cap X^{(\beta)} = \{p\}$ .

Now suppose that  $h$  is a homomorphism of  $B$  into a complete Boolean algebra  $C$ . We define a mapping  $h^*$  of  $B^*$  into  $C$  inductively (for convenience, we will write  $h^*(p)$  instead of  $h^*({p})$ ). If  $p$  is an isolated point of  $X$ , let  $h^*(p) = h(b_p)$ . If  $p$  is an isolated point of

$X^{(\beta)}$  and  $h^*(q)$  is defined for each  $q \in X \sim X^{(\beta)}$ , let

$$h^*(p) = h(b_p) \Pi \{\overline{h^*(q)} : q \in i(b_p) \sim X^{(\beta)}\}.$$

If  $S \subset X$ , let  $h^*(S) = \Sigma\{h^*(p) : p \in S\}$ .

Next, we prove that for every ordinal  $\beta$ ,

$S_\beta$ : (i) if  $b \in B$  and  $i(b) \cap X^{(\beta)} = \phi$ , then  $h^*(i(b)) = h(b)$ ;

(ii) if  $b \in B$  and  $i(b) \cap X^{(\beta)} = \{p\}$ , then

$$h(b) \Pi \{\overline{h^*(q)} : q \in i(b) \sim X^{(\beta)}\} = h^*(p).$$

Since  $X$  is Hausdorff, the truth of (ii) implies that if  $p, q \in X$  and  $p \neq q$ , then  $h^*(p)$  is disjoint from  $h^*(q)$ . Thus, if  $S_1$  and  $S_2$  are subsets of  $X$  and  $S_1 \cap S_2 = \phi$ , then  $h^*(S_1)$  and  $h^*(S_2)$  are disjoint. Since  $h^*$  is completely additive by definition, (i) then implies that  $h^*$  is a complete homomorphism of  $B^*$  into  $C$ , and  $h^* \circ i = h$ .

$S_0$  is clearly true, since  $X^{(0)} = X$ . Now suppose that  $\beta$  is an ordinal such that  $S_\alpha$  is true for every ordinal  $\alpha$  such that  $\alpha < \beta$ , and that  $b$  is an element of  $B$  such that  $i(b) \cap X^{(\beta)} = \phi$ . If  $\beta$  is a limit ordinal, then since  $i(b)$  is compact, there is an ordinal  $\alpha$ ,  $\alpha < \beta$ , such that  $i(b) \cap X^{(\alpha)} = \phi$ ; hence,  $h^*(i(b)) = h(b)$ . If  $\beta$  is not a limit ordinal, and  $i(b) \cap X^{(\beta-1)} \neq \phi$ , then  $i(b) \cap X^{(\beta-1)}$  is finite, since it is compact and discrete. We can, without loss of generality, assume that  $i(b) \cap X^{(\beta-1)} = \{p\}$ . Then, by  $S_{\beta-1}(i)$ ,  $h^*(p) = h(b) \Pi \{\overline{h^*(q)} : q \in i(b) \sim X^{(\beta-1)}\}$ ; it follows that

$$h(b) \leq h^*(p) + \Sigma\{h^*(q) : q \in i(b) \sim X^{(\beta-1)}\},$$

and thus,  $h^*(p) \leq h(b) \leq h^*(i(b))$ . Moreover, if  $q \in i(b) \sim X^{(\beta-1)}$ , there is an ordinal  $\alpha$ ,  $\alpha < \beta - 1$ , and a  $c \in B$ ,  $c \leq b$ , such that  $h^*(q) \leq h(c)$ ; thus,  $h(b) = h^*(i(b))$ . Hence, if  $S_\alpha$  is true for every ordinal  $\alpha$  such that  $\alpha < \beta$ , then  $S_\beta(i)$  is true.

Next, suppose that  $b$  is an element of  $B$  such that  $i(b) \cap X^{(\beta)} = \{p\}$ . Using  $S_\beta(i)$ , we have

$$\begin{aligned} h(b) \Pi \{\overline{h^*(q)} : q \in i(b) \sim X^{(\beta)}\} \\ &= [h(bb_p) + h^*(i(bb_p))] \Pi \{\overline{h^*(q)} : q \in i(b) \sim X^{(\beta)}\} \\ &= h(bb_p) \Pi \{\overline{h^*(q)} : q \in i(bb_p) \sim X^{(\beta)}\} \Pi \{\overline{h^*(q)} : q \in i(bb_p)\} \\ &= h(bb_p) \Pi \{\overline{h^*(q)} : q \in i(bb_p) \sim X^{(\beta)}\}. \end{aligned}$$

In the same way, we can show that

$$h(b_p) \Pi \{\overline{h^*(q)} : q \in i(b_p) \sim X^{(\beta)}\} = h(bb_p) \Pi \{\overline{h^*(q)} : q \in i(bb_p) \sim X^{(\beta)}\}.$$

This completes our proof.

**REMARK.** It is easily seen that there is only one complete homo-

morphism of  $B^*$  into  $C$  which is an extension of  $h$ , since such an extension must have the property that if  $p \in X$ , then

$$h^*(p) = \prod \{h(b) : p \in i(b)\},$$

and if  $S \subset X$ , then  $h^*(S) = \Sigma \{h^*(p) : p \in S\}$ .

It remains only to be shown that a non-superatomic Boolean algebra has no free complete extension.

**LEMMA.** *If the Boolean algebra  $B$  has a free complete extension, then so does every subalgebra of  $B$ .*

*Proof.* Suppose that  $B$  has a free complete extension  $B^*$ , that  $i$  is the associated isomorphism of  $B$  into  $B^*$ , and that  $B'$  is a subalgebra of  $B$ . Let  $B^{**}$  be the complete subalgebra of  $B^*$  which is completely generated by  $i[B']$ . If  $h'$  is a homomorphism of  $B'$  into the complete Boolean algebra  $C$ , then, according to a result of Sikorski ([8], p. 112),  $h'$  can be extended to a homomorphism  $h$  of  $B$  into  $C$ . Since  $B^*$  is the free complete extension of  $B$ , there is a complete homomorphism  $h^*$  of  $B^*$  into  $C$  such that  $h^* \circ i = h$ . The restriction of  $h^*$  to  $B^{**}$  is a complete homomorphism of  $B^{**}$  into  $C$ , and for every  $b \in B'$ ,  $h^*(i(b)) = h'(b)$ .

**THEOREM.** *A Boolean algebra has a free complete extension if and only if it is superatomic.*

*Proof.* It was shown above that every superatomic Boolean algebra has a free complete extension. Now suppose that  $B$  is a nonsuperatomic Boolean algebra. According to the theorem of § 2,  $B$  must have a subalgebra which is an infinite free Boolean algebra. It follows immediately from the result of Gaifman ([3]) and Hales ([4]) mentioned in our introduction, and the above lemma, that  $B$  has no free complete extension.

4. The free  $\alpha$ -extensions of superatomic Boolean algebras. F. M. Yaqub showed in [10] that if a Boolean algebra  $B$  has a free  $\alpha$ -extension  $B_\alpha$  which is  $\alpha$ -representable (that is, if  $B_\alpha$  is the image of an  $\alpha$ -field of sets under an  $\alpha$ -complete homomorphism), then  $B_\alpha$  is isomorphic to an  $\alpha$ -field of sets, and if  $\alpha \geq 2^{\aleph_0}$ , then  $B$  is superatomic. The results of § 3 enable us to prove the following converse of this statement.

**THEOREM.** *If  $B$  is a superatomic Boolean algebra, then the free  $\alpha$ -extension of  $B$  is isomorphic to an  $\alpha$ -field of sets.*

*Proof.* It was shown in § 3 that a superatomic Boolean algebra  $B$  has a free complete extension  $B^*$  which is a complete field of sets. For each cardinal  $\alpha$ , let  $\beta_\alpha$  denote the  $\alpha$ -complete subfield of  $B^*$  which is  $\alpha$ -generated by  $B$ . Suppose that  $h$  is a homomorphism of  $B$  into an  $\alpha$ -complete Boolean algebra  $C$ . Let  $C'$  denote the normal completion of  $C$ , and let  $h^*$  be the complete homomorphism of  $B^*$  into  $C'$  which is an extension of  $h$ .  $h^*$  carries  $B_\alpha$  into  $C$  since  $B$   $\alpha$ -generates  $B_\alpha$ ,  $h^*[B] \subset C$ , and  $C$  is an  $\alpha$ -complete,  $\alpha$ -regular subalgebra of  $C'$ . The restriction of  $h^*$  to  $B$  is thus an  $\alpha$ -complete homomorphism of  $B_\alpha$  into  $C$ , and is an extension of  $h$ . Hence  $B_\alpha$  is the free  $\alpha$ -extension of  $B$ .

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Robert James Blattner, <i>Group extension representations and the structure space</i> .....	1101
Glen Eugene Bredon, <i>On the continuous image of a singular chain complex</i> .....	1115
David Hilding Carlson, <i>On real eigenvalues of complex matrices</i> .....	1119
Hsin Chu, <i>Fixed points in a transformation group</i> .....	1131
Howard Benton Curtis, Jr., <i>The uniformizing function for certain simply connected Riemann surfaces</i> .....	1137
George Wesley Day, <i>Free complete extensions of Boolean algebras</i> .....	1145
Edward George Effros, <i>The Borel space of von Neumann algebras on a separable Hilbert space</i> .....	1153
Michel Mendès France, <i>A set of nonnormal numbers</i> .....	1165
Jack L. Goldberg, <i>Polynomials orthogonal over a denumerable set</i> .....	1171
Frederick Paul Greenleaf, <i>Norm decreasing homomorphisms of group algebras</i> .....	1187
Fletcher Gross, <i>The 2-length of a finite solvable group</i> .....	1221
Kenneth Myron Hoffman and Arlan Bruce Ramsay, <i>Algebras of bounded sequences</i> .....	1239
James Patrick Jans, <i>Some aspects of torsion</i> .....	1249
Laura Ketchum Kodama, <i>Boundary measures of analytic differentials and uniform approximation on a Riemann surface</i> .....	1261
Alan G. Konheim and Benjamin Weiss, <i>Functions which operate on characteristic functions</i> .....	1279
Ronald John Larsen, <i>Almost invariant measures</i> .....	1295
You-Feng Lin, <i>Generalized character semigroups: The Schwarz decomposition</i> .....	1307
Justin Thomas Lloyd, <i>Representations of lattice-ordered groups having a basis</i> .....	1313
Thomas Graham McLaughlin, <i>On relative coimmunity</i> .....	1319
Mitsuru Nakai, <i><math>\Phi</math>-bounded harmonic functions and classification of Riemann surfaces</i> .....	1329
L. G. Novoa, <i>On <math>n</math>-ordered sets and order completeness</i> .....	1337
Fredos Papangelou, <i>Some considerations on convergence in abelian lattice-groups</i> .....	1347
Frank Albert Raymond, <i>Some remarks on the coefficients used in the theory of homology manifolds</i> .....	1365
John R. Ringrose, <i>On sub-algebras of a <math>C^*</math>-algebra</i> .....	1377
Jack Max Robertson, <i>Some topological properties of certain spaces of differentiable homeomorphisms of disks and spheres</i> .....	1383
Zalman Rubinstein, <i>Some results in the location of zeros of polynomials</i> .....	1391
Arthur Argyle Sagle, <i>On simple algebras obtained from homogeneous general Lie triple systems</i> .....	1397
Hans Samelson, <i>On small maps of manifolds</i> .....	1401
Annette Sinclair, <i><math> \varepsilon(z) </math>-closeness of approximation</i> .....	1405
Edsel Ford Stiel, <i>Isometric immersions of manifolds of nonnegative constant sectional curvature</i> .....	1415
Earl J. Taft, <i>Invariant splitting in Jordan and alternative algebras</i> .....	1421
L. E. Ward, <i>On a conjecture of R. J. Koch</i> .....	1429
Neil Marchand Wigley, <i>Development of the mapping function at a corner</i> .....	1435
Horace C. Wiser, <i>Embedding a circle of trees in the plane</i> .....	1463
Adil Mohamed Yaqub, <i>Ring-logics and residue class rings</i> .....	1465
John W. Lamperti and Patrick Colonel Suppes, <i>Correction to: Chains of infinite order and their application to learning theory</i> .....	1471
Charles Vernon Coffman, <i>Correction to: Non-linear differential equations on cones in Banach spaces</i> .....	1472
P. H. Doyle, III, <i>Correction to: A sufficient condition that an arc in <math>S^n</math> be cellular</i> .....	1474
P. P. Saworotnow, <i>Correction to: On continuity of multiplication in a complemented algebra</i> .....	1474
Basil Gordon, <i>Correction to: A generalization of the coset decomposition of a finite group</i> .....	1474