An interactive system for finding complementary literatures: a stimulus to scientific discovery

Don R. Swanson* & Neil R. Smalheiser†
*Division of the Humanities, The University of Chicago
1010 E. 59th St., Chicago, IL 60637
†Department of Pediatrics, MC 5058, The University of Chicago
5841 S. Maryland Ave., Chicago, IL 60637

Abstract

An unintended consequence of specialization in science is poor communication across specialties. Information developed in one area of research may be of value in another without anyone becoming aware of the fact. We describe and evaluate interactive software and database search strategies that facilitate the discovery of previously unknown cross-specialty information of scientific interest. The user begins by searching MEDLINE for article titles that identify a problem or topic of interest. From downloaded titles the software constructs input for additional database searches and produces a series of heuristic aids that help the user select a second set of articles complementary to the first set and from a different area of research. The two sets are complementary if together they can reveal new useful information that cannot be inferred from either set alone. The software output further helps the user identify the new information and derive from it a novel testable hypothesis. We report several successful tests and applications of the system.

1. Introduction and background

An important problem in the growth of knowledge is brought to light by the following type of literature structure: One set of articles (AB) reports an interesting association between variables A and B, a different set of articles (BC) reports a relationship between B and C, but nothing at all has been published concerning a possible link between A and C, even though such a link if validated would be of scientific interest [6, 30]. For example, "A" might represent intake of a substance that induces a specific physiological change B, which in turn influences disease or body organ C. In broader terms, two

literatures such as AB and BC are complementary if useful information can be inferred by considering them together that cannot be inferred from either one alone. If, furthermore, the two literatures are mutually isolated in that the authors and readers of one literature are not acquainted with the other, and vice versa, as may often be the case for two different specialties, then no one at all may be in a position to notice the implication that A and C might be related. To detect literature pairs that are mutually isolated, we examine the citation pattern [7]. If two literatures are "noninteractive" — that is, if they have never (or seldom) been cited together, and if neither cites the other, — then it is possible that scientists have not previously considered both literatures together [25, 35]. The two conditions, complementarity and noninteraction, describe a model structure that shows how useful information can remain undiscovered even though its components consist of public knowledge. Figure 1 illustrates how multiple intermediate literatures might link a given A and C.

The concept of "undiscovered public knowledge" was developed and exemplified in 1986 [28, 29] based on an actual structure in the biomedical literature similar to the AB-BC model shown in Figure 1. Articles on Raynaud's disease (C) and articles on eicosapentaenoic acid (A) when considered together were suggestive that Raynaud patients might benefit from dietary fish oils rich in eicosapentaenoic acid [29]. One B-linkage, for example, was: dietary eicosapentaenoic acid can decrease *blood viscosity* (B); abnormally high *blood viscosity* has been reported in patients with Raynaud's disease. Neither of the two literatures (A, C) cited or mentioned the other, nor has extensive searching turned up any prior suggestions that dietary fish oils might influence Raynaud's disease. An independent clinical trial by medical researchers [2] subsequently corroborated the predicted beneficial effects, as discussed in [5, 37]. This first structure was found more or less by accident, but inspired an ongoing effort to systematize the search process [32, 36], corroborate and replicate the structure [8], model it [3, 36], extend it [3, 4, 8], trace historical antecedents [4], and examine citations to the project itself [27, 37].

A second example of complementary noninteractive literatures began with the literature on migraine (C), and subsequently identified a literature showing that magnesium deficiency (A) led to certain physiological effects (B) that, in a different context, were associated with migraine [31]. Eleven intermediate effects, B, provided the linkage. (Two such linkages are, for example: magnesium can inhibit *spreading*

depression in the cortex, and *spreading depression* may be implicated in migraine attacks; magnesium-deficient rats have been used as a model of *epilepsy*, and *epilepsy* has been associated with migraine). Remarkably, even though the literatures on magnesium and migraine that were identified as having extensive indirect linkages consisted of more than 60 articles each, neither literature cited or mentioned the other. Moreover at that time (1988) there were almost no records in the entire MEDLINE database that contained both of the words "migraine" and "magnesium". Since 1988 [31], more than 12 different groups of medical researchers have reported a systemic or local magnesium deficiency in migraine or a favorable response of migraine patients to dietary supplementation with magnesium [21, 37]. There is also one recent report of negative results [26].

To date we have found and described seven examples of complementary pairs of literatures, using progressively improved methods for finding them [21-24, 29, 31, 33]. In each case we discerned a novel testable hypothesis that was implicit in a pair of literatures considered together, but not previously made explicit in published form. Each structure was found through extensive searching, exploring, and reading biomedical literature [34]. The hypotheses evoked by these procedures can be evaluated by: 1) their inherent plausibility, 2) their acceptance for publication in a refereed biomedical journal; 3) whether they stimulate biomedical researchers to conduct clinical trials or laboratory experiments, and 4) whether the hypotheses are corroborated as a result of such tests. For the two earliest cases [29, 31] all four criteria appear to have been met [2, 21, 37].

Our goal has been to create interactive software and database search strategies that can facilitate the discovery of complementary structures in the published literature of science. The universe of literature or search-space under consideration is limited only by the coverage of the major scientific databases, though we have focused primarily on the biomedical field and the MEDLINE database (8 million records). In 1991, a systematic approach to finding complementary structures was outlined and became a point of departure for software development [36]. The system that has now taken shape is based on a 3-way interaction between computer software, bibliographic databases, and a human operator. The interaction generates information structures that are used heuristically to guide the search for promising complementary literatures. In this paper we describe and evaluate the experimental computer software, which we call ARROWSMITH, and we explain how it functions within the system.

2. Approach and overview

For the migraine study [31] we analyzed the form of the eleven relationships between A and B and between B and C that we had found [36, p 282]. (For example, some variant of "can or might influence" occurred repeatedly.) It was clear from the outset that, even if we were able to fit most relationships into a limited number of seemingly simple patterns, few or none of them were transitive; they were, however, often suggestive of a plausible new inference. But to recognize relationships within the natural language text of titles and abstracts and to draw inferences from them requires both common sense and extensive background knowledge. We have not attempted to formalize or automate such tasks. Our approach is based instead on automated procedures that present, for human observation, suggestive juxtapositions of natural-language extracts (mainly titles, at present) from database records. We attempt to stimulate, rather than codify, the discovery process.

The user of the system begins by choosing a question or problem area of scientific interest that can be associated with a literature, C. The ultimate target of the ensuing search is a second literature, A, complementary to literature C. Two main procedures (I and II) implement the foregoing approach in a working experimental system. *Procedure I* operates on a single specified "source" literature, C, identified by a database search of title words or phrases. Figure 2 is a schematic diagram of title-word pathways from literature C, proceeding via multiple intermediate B-terms that co-occur with title-word "C", to various possible target title words denoted A1, A2, A3 .. etc., each of which co-occurs with one or more B-terms. There can be, potentially, thousands of intermediate B-terms that link to C, and, for each B, thousands of possible candidates for A that link to B. The problem of searching for one (or a few) initially unknown Ai within the entire MEDLINE database presents a formidable explosion of possibilities. The interactive system we describe evades this explosion by first restricting, by various means, the number of different B-linkages to be traversed. From the resulting list of "A-candidates", the user chooses one Ai judged to be biologically plausible. (Alternatively, the user may choose A on some other basis and simply bypass *Procedure I*.)

Procedure II starts anew from *two* pre-selected literatures, A and C (irrespective of how A was chosen). Focusing on a single target literature, A, makes it feasible now to develop a much less restricted list of title-word pathways that connect A to C. This

procedure aims to identify all title-word pathways that might provide clues to the presence of complementary arguments within those literatures. The output of *Procedure II*, a structured title-display (plus journal citation), serves as a heuristic aid to identifying word-linked titles and serves as an organized guide to the literature.

ARROWSMITH (and its user) may be seen as a problem-generating system [16, 17]. The user chooses a relatively broad initial problem area (e.g. a disease for which neither cause nor cure is known) and is guided by *Procedure I* toward promising complementary literatures and by *Procedure II* toward a series of more specific problems concerning biological pathways that might constitute mechanisms of action, and ultimately toward a problem presented to the experimentalist in the form of a plausible testable hypothesis.

2.1 Procedure I: Forming a ranked list of A-word candidates

In this section we describe *Procedure I* applied to a specific example in which C is taken as the pre-1988 literature on migraine.

Step 1. Conduct a MEDLINE search for all titles that contain the word "migraine"; download these titles into a local computer file (FILE C). Derive automatically from FILE C a list of the unique words that it contains (that is, words that co-occur in titles with "migraine"). This list contains all possible candidates for B-words, (including potentially interesting words such as "inflammatory", "platelet", "prostaglandin", "serotonin", "vasospasm") but it contains also many unsuitable words. In order to evade an explosion of search-paths and to limit the output to manageable size, four types of restrictions are introduced, the first being: i) Words that are predictably unsuitable as B-candidates are excluded (e.g. not only non-topic words such as "able", "about", "above", but also words that are vague or too general such as "clinical", "comparative", "drugs", "evidence", "experimental", "role", "treatment", "studies") [36]. A pre-compiled exclusion list, or "stoplist" is provided to the computer. The list is human-constructed on the basis of judgment applied *a priori* concerning the suitability of each word, and at present consists of about 5000 words.

Step 2. Each of the remaining B-word candidates is then searched in MEDLINE to determine the total number of titles in which it occurs. Restriction ii): These words are further screened automatically to retain only those that occur with greater relative frequency in migraine titles than in titles from MEDLINE as a whole. The latter

frequency is determined from the information displayed in the online search which shows each search statement and the corresponding number of items found. More specifically, we retain only words for which the probability is small that a random allocation of words to titles could lead to a number of co-occurrences with "migraine" equal to or greater than the observed number [1]. (The cutoff probability in our migraine example is 0.09, as calculated from a Poisson distribution, ignoring multiple occurrences of a given word within the same title).

Step 3. We introduce Restriction iii): the human operator examines the filtered list of B-terms, and removes entries that are judged not suitable — e. g. words that should be put on the stoplist, or possibly words too broad to be useful in the particular problem considered. Each word that remains becomes the basis for a new MEDLINE title-search.

Restriction iv is introduced into the search strategy: Each set of records formed by searching titles for each B-word is to be narrowed down to certain *categories* of records (chosen in advance) that are likely to contain target words of particular interest. This restriction is methodologically important for it provides the user flexibility in conducting an exploratory process that may in many respects model the process of scientific inquiry [11]. To date, most of our restriction categories have focused on exogenous agents because of their potential for experimental manipulation in clinical tests. Thus, categories such as deficiencies, dietary factors, toxins, or various subcategories of drugs or environmental factors might be selected, strategies that can be designed and tested in advance and built into the system [36]. In the present migraine example, the strategy was designed to restrict the output to dietary factors or deficiencies induced by dietary deprivation. Detailed search statements are given in [36]. Commands to form the intersection of the restriction set with each B-word set and a command to form the union of those intersections (U), are constructed automatically.

Step 4. The resulting search is uploaded into MEDLINE and executed. All titles that correspond to set U are then downloaded to FILE U in the local computer. FILE U is converted to a list of word occurrences (potential A-words), again using the stoplist as a filter, repeating restriction i. Each A-occurrence is attached to the B-word that generated it, thus forming an A-B list that is used at a later point. It is also used immediately to create a list of unique A-words for the database search of Step 5.

Step 5. A database title-search is conducted for each unique A-word in order to determine, for each A, the number of A-word titles within the restriction category.

Repeating restriction ii): the A-words are filtered according to probabilistic criteria, but now based on their co-occurrences with each B-word (rather than with "migraine"). The A-words thus selected constitute the list of A-candidates. Each candidate is then assigned a rank according to the number of different B-words in the AB-BC co-occurrence linkages in which it participates, as illustrated in Figure 2. This ranking algorithm is based on a presumption that the greater the number of B-term linkages, the greater the chance that some of them will be biologically important. The candidate list is displayed for the human operator to use as a heuristic device (Fig. 3).

Step 6. From the ranked list, expert judgment is brought to bear in choosing words that appear to be the best candidates for assisting the discovery of complementary arguments, and so for defining a literature (A) complementary to that of C. Any one choice of A-word from the candidate list can provide input to *Procedure II* (Section 2.2).

The leftmost list in Figure 3 shows the first 24 ranked A-terms for our migraine example. "Magnesium" is ranked first. Not only is it of high rank, it is biologically highly plausible. Magnesium is an essential element in the human diet and is well known as a modulator of neurotransmission. By these criteria "magnesium" emerged as the most promising A-word candidate.

Other words on the A-candidate list also might merit further exploration. Some of them are, however, too broad to be useful if taken alone ("hormone", "pressure", "lipid(s)", "hepatic", "membrane"). For reasons of practicality, the A-list is at present limited to single words, even though phrases may often be more appropriate and informative. However, the titles in which any particular A-word occurs (in File U) can be examined to determine whether a consistently more specific context can be identified. For example, we found that "hormone" and its B-linkages referred in most cases to "growth hormone"; the B-linkages, however, did not appear to be important enough to pursue further. One could determine also whether a single letter such as "e" refers consistently to vitamin E, apolipoprotein E, E-coli, or hepatitis E, and so on.

2.2 Procedure II: Forming a list of B-terms and a title display

This procedure develops a greatly expanded list of B-terms for a given A and C. The probabilistic and category restrictions (ii and iv) are dropped, and phrases of up to 6 contiguous words are included. "A" represents any single agent which may have been

taken from the *Procedure I* list of A-candidates, or "A" may simply be based on an informed scientific conjecture concerning a possible A-C relationship.

Procedure II should always be preceded by a database search for all records that contain both A and C (not restricting the search to just titles), in order to identify any A-C or A-B-C relationships that are already explicitly published. Such known B-linkages should be investigated in advance of executing *Procedure II* to avoid unknowingly rediscovering them as indirect linkages; *Procedure II* can then focus on relationships that are either novel or at least cannot be found by conventional searching. Understanding strategies used in conventional searching is important at this point; finding the "direct" literature is not always straightforward [12, 13]. The citation interaction pattern also can play a key role in determining whether an A-C relationship exists and is already known, a process described in more detail elsewhere [35].

The output of *Procedure II* is to be a printed display of titles from the A and C literatures organized according to the words, B, that they have in common. Figure 4 is a schematic flowchart of the process that leads to this output, a process that begins with downloading the two sets of titles (and journal citations) for literatures A and C. For the migraine application (based on pre-1988 literature), MEDLINE was used to create a local file (C) of all titles (about 2800) that contain the word "migraine", and a file (A) of all titles (about 8000) that contain the word "magnesium". No title contained both words. The computer then produced a list of all words and phrases (about 200, after excluding stoplist words), called the "B-LIST", each of which appeared in at least 2 migraine titles and 2 magnesium titles.

Application of the stoplist to phrases merits further comment. The appropriateness of the stoplist for many words depends on the context in which they are used. "Protein", for example, is too broad to be useful, and so is put on the stoplist. But individual proteins are not, and the names of some of these include the word "protein", such as "amyloid beta-protein" or "protein kinase C". We therefore divide the stoplist into two parts, a short list of prepositions and other connectives and a long (5000-word) list. We apply only the short stoplist to each word in a phrase. Only if every remaining word in the phrase is on the long stoplist is the phrase dropped. (Figure 4).

The B-LIST is next edited by removing redundancies and non-useful terms, resulting, for the migraine/magnesium case, in cutting the list from 200 to 150 terms. The editing process in general may include adding, deleting, removing redundancies, or revising

entries in order to compensate for certain limitations in the mechanized rules.

After the editing has been completed, the computer produces a display or printed output that shows titles within title-file A that share B-terms with titles in file C, organized alphabetically by the 150 B-terms. A similar display is created for title-file C, thus facilitating a comparison of titles A (magnesium) with titles C (migraine) that have one or more B-words or phrases in common. Figure 5 shows the general format of the display and some of the more interesting titles selected for their suggestiveness of complementarity. This title display is the principal product of ARROWSMITH. In our example it contained altogether about 920 migraine titles and 1350 magnesium titles.

In general, portions of the title-display output that appear promising on the basis of expert judgment then become a heuristic point of departure for reviewing literatures A and C in order to identify complementary statements or arguments (for example, AB-BC relationships) that lead to novel testable hypotheses.

A study of the output display for magnesium and migraine revealed about 40 B-terms (listed in Figure 6) that merit further investigation because they appear, from some of the titles with which they are associated, to be related to both magnesium and migraine in a way that suggests a physiological linkage.

3. Evaluating ARROWSMITH

In this paper we try to make clear how and why we found ARROWSMITH useful in a search for complementary literatures. We have presented a step by step process and detailed examples of output to permit others to form a reasonable judgment concerning usefulness.

Prior to designing ARROWSMITH, we had available three completed and published analyses of complementary noninteractive literatures [29, 31, 33]. These studies provide an opportunity to determine whether ARROWSMITH can at least be helpful in rediscovering complementary structures already known by the user to exist. Such an outcome cannot be taken for granted without being put to a test -- principally because it is not otherwise obvious that article titles alone contain enough information to put the user on the track of complementary literatures.

For the migraine case study exemplified in the preceding section, we have noted that "magnesium" was first on the ranked list of terms produced automatically as the output of

Procedure I. The title-word co-occurrence data that led to this ranking was not generated at the time of the original study; magnesium was chosen on quite different grounds at that time. Not only did magnesium rank high on the list of A-candidates, but within the B-list generated by *Procedure II* (Figure 6), one can recognize ten of the eleven connections identified originally in the 1988 migraine/magnesium study (the eleventh did not co-occur with "magnesium" as a title-word in MEDLINE). In addition, a substantial number of new and plausible candidates for B-terms also appeared on the list. The 19 words and phrases marked with an asterisk in Figure 6 correspond, with redundancies removed, to the 10 terms discussed in the earlier study [31]. Thus, using *Procedure II*, almost all of the originally reported B-term connections were produced automatically, and in a matter of hours, replacing weeks-long literature-searching and exploration that was previously required.

Up to this point, production of the ranked A-list and the B-list are automatic, provided the user chooses the same search- restriction categories and strategy (based on terms related to dietary intake) as we exemplified. Users do have the option of changing this feature of the exploratory process however. In the next stage, the production of the output title display (of which a small part is shown in Figure 5) is also automatic, for it is fully defined by the B-list and the original set of downloaded titles. Figure 5 itself was not automatically produced; the 67 titles shown were selected from the complete display of about 2270 titles. This selection process is of course sensitive to what the user is looking for, and other users might not see the same, or as many, linked titles in the output display as we found. However, we invite readers to study Figure 5 closely and try to form a judgment of the effectiveness of these word linked titles in suggesting a possible link between magnesium deficiency and migraine. Successful use of the complete title display does not depend on recognizing or selecting all of the titles we selected, but only on seeing enough linked titles to impel further searching and analysis. Thus, the method is probably quite robust with respect to individual variability among users. Accordingly, we believe that the success of this retrospective application of *Procedure I* in discovering an already-known structure provides a reasonable basis for judging how the system would have performed had the structure not been known in advance. That is, the opportunity for favorably distorting the outcome because the users knew what to look for is relatively limited.

The application of *Procedure I* to the pre-1986 literature on Raynaud’s disease [29]

was similarly successful, except that here the context revealed in File U played a more central role. "Oil", one of the high-ranking but fairly broad words on the A-list (Fig. 3) occurred (within File U) repeatedly in the same, and much narrower, context defined by "dietary fish oil" (or equivalent terms). Figure 6 shows a B-list for the Raynaud's disease analysis. We produced substantially the same outcome as in the original analysis reported in 1986 [28, 29]. In addition, the main findings of that analysis have been largely replicated, as well as extended, independently by other researchers [8].

The success of ARROWSMITH in the above two case studies was not matched in the third study, that of somatomedin C and arginine [33]. This attempt failed because there were no paired titles that were suggestive of complementary arguments within the corresponding literatures. This failure to re-discover an already known structure underscores an important point. We cannot and do not claim that the procedures we have developed will always be successful, even in the hands of a prescient user. Some of the many reasons why our procedures, as presently designed, might fail to reveal complementary literatures that do exist are discussed in section 5.2.

The next section of this paper can also be seen as an evaluation of ARROWSMITH (*Procedure II*). But in this case, the test is focused on producing novel results rather than on finding structures that we previously had discovered using more conventional literature search methods.

4. Examples that use Procedure II independently of Procedure I.

Procedure II will be useful independently of *Procedure I* if the user already has formed hypotheses concerning plausible A-literatures. For example, a biomedical researcher may have reason to think that a particular A-term is related to C without necessarily knowing the intermediate pathways or mechanisms by which A and C are linked. *Procedure II* can be regarded as a "higher order Medline search" (because it finds 2nd-order indirect title-word connections). The following three examples fit this pattern. The first two examples, on Alzheimer's disease (AD), show how previously unknown connections can be discovered even between two literatures already known to interact in other respects.

4.1 Case example 1: Indomethacin and Alzheimer's disease (AD).

The literatures corresponding to indomethacin (A) and Alzheimer's disease (C) intersect and are interactive. Indeed, indomethacin appears to have a protective effect against AD, as evidenced by epidemiologic and clinical data [22]. Nevertheless indomethacin, an inhibitor of prostaglandin synthesis, affects many organ systems and its effects have been reported in the literatures of many diverse specialties. Therefore it is not an easy task to find all known effects of indomethacin which are likely to be relevant to patients with AD. *Procedure II* offers a useful aid to solving this problem by displaying numerous plausible indirect (A-B-C) title-word linkages between the two literatures on indomethacin and AD. In this case ARROWSMITH found 103 B-terms, of which 5 referred to substances or physiologic processes affected by indomethacin in a way that, as indicated separately in the AD literature, might possibly ameliorate AD [22]. In addition, we found a possible adverse effect: indomethacin had a well-documented anti-cholinergic action, and separately it was clear from the AD literature that one would expect anti-cholinergic action to affect AD patients adversely by exacerbating cognitive dysfunction. The possibility that indomethacin might have adverse side effects in AD patients apparently had not been considered explicitly in any scientific publication and so we brought this to the attention of neuroscientists [22].

4.2 Case Example 2: Estrogen and Alzheimer's disease

Even though it has become relatively well established that estrogen replacement therapy for postmenopausal women results in a lower incidence of AD, the mechanism of such beneficial effects is not understood. We used *Procedure II* to develop a list of potential B-linkages between estrogen and AD; there were several hundred B-terms that appeared in at least 2 titles in each literature. About 8 of these terms (calbindin D28K, cathepsin D and other proteases, superoxide dismutase, antioxidants, apolipoprotein E, glutamate, cytochrome C oxidase subunit III) refer to substances that are known to be modulated by estrogen and are separately known to be implicated in AD, but which have not been investigated as estrogen targets in the context of AD. In the process of investigating the literature identified by the output title display, we encountered intriguing reports indicating that estrogen has antioxidant activity. There is also an extensive AD literature on free radicals (groups of atoms, usually highly active, that have one or more unpaired electrons) which are thought to play a role in the development of AD. Because

antioxidants would tend to counteract such effects, it is remarkable that there was no evidence in the database-accessible literature that AD researchers were aware of this possible mechanism for estrogen's beneficial effects [23]. After our paper was submitted for publication [23], one study did appear which mentioned this link.

4.3 Case Example 3: Phospholipases and Sleep

The hypothesis that phospholipases may regulate sleep has been raised implicitly (phospholipases may regulate prostaglandin synthesis and several prostaglandins are endogenous sleep modulators), but this idea has not been investigated experimentally nor discussed explicitly in the biomedical literature. We employed *Procedure II* in three searches using "sleep" as the C-literature and "phospholipase A2", "phospholipase C", or "phospholipase D" as A-literatures. (In this case we found that most B-terms did not represent substances formed by phospholipase activity, but rather substances that stimulate or inhibit phospholipases.) We found a number of cytokines and neuromodulators among the B-terms, notably the major sleep-promoting substances interleukin 1β, tumor necrosis factor, and endotoxin/lipopolysaccharide. These substances stimulate phospholipase A2, C, and D activities in various systems, and this stimulation is thought to be required for at least some of their biological activities. Thus, *Procedure II* generated a list of promising agents whose effects on sleep may involve phospholipases, and we suggest testing whether specific phospholipase inhibitors inhibit the sleep-promoting effects of these agents [24].

5. Discussion

5.1. Intelligence, implanted structures, and the role of heuristics.

ARROWSMITH provides three stages of output information structures that serve as heuristic guides to complementary scientific arguments within the literature: i) the list of A-candidates (Figure 3); ii) the B-LIST; and iii) the title display organized by B-terms (Figure 5). The process is heuristic in that human choices at each stage not only are assisted by the displayed structures [40], but these choices in turn influence the outcome of each later stage. Each cycle through the three stages provides valuable information for

a retry, either with a new choice from the same A-candidate list, or possibly with a new A-list derived from a different restriction category.

ARROWSMITH possesses no algorithm for recognizing "interesting" relationships such as transitivity or complementarity, but it *seems* to have such a capability. The density of interesting title relationships revealed by the stage iii display appears to be remarkably greater than the density of interesting relationships among titles selected randomly even from two complementary literatures. The consequent impression of intelligence arises primarily from three sources: the stoplist, the search strategy restriction category, and the organization of the output display. These structures are human created, then supplied to the computer, and can be thought of as implanted intelligence. ARROWSMITH filters and organizes title data based on these implanted structures.

5.2. Limitations, improvements and future directions.

The use of title-words as a basis for detecting complementary literatures is both a strength and a weakness of ARROWSMITH. The advantage of titles lies in the fact that they provide a constrained context within which the linkages between A and B terms, and between B and C terms, tend to be biologically meaningful and easily perceived by the viewer, thus facilitating the recognition of potential complementarity. On the other hand, ARROWSMITH at present does not attempt automatic linkage detection in abstracts or subject headings. Other investigators have shown that such information can be exploited. Using full MEDLINE records (1983-1985 only), no restriction categories, and several statistical criteria, Gordon and Lindsay have confirmed that fish-oil is a high-ranking A-candidate in the A-B-C model for Raynaud's disease [8].

Each of ARROWSMITH's output heuristic information structures serves also as a source of feedback that is potentially useful for improving the system, evaluating it, and perhaps for stimulating ideas that can lead to better models and theories. Within the framework of the present design, numerous incremental improvements appear to be possible through augmenting the stoplist, improving phrase recognition by allowing for more variation in word morphology and word position, organizing and grouping B-terms with the help of subject headings, extending the A-candidate list to include phrases, and developing a synonym-recognition capability.

The most practical and straightforward approach to improving ARROWSMITH consists in juxtaposing pairs of titles not only on the basis of words they have in common but in addition by common subject headings in the two respective MEDLINE records. This kind of linkage supplies additional context for paired titles that may be meaningful to the expert observer. Moreover, linking titles by common subject headings may also reduce the number of near-synonymous or equivalent structures that are missed by word-matching.

On a longer range basis, we envision applying ARROWSMITH to databases other than MEDLINE and particularly to records that may be derived from different databases. For such applications, the Metathesaurus® of the Unified Medical Language System® (UMLS) offers a potentially valuable resource for developing a hierarchy/synonym-recognition capability. The 1996 Metathesaurus is a synthesis of 38 different source vocabularies (one of which is *Medical Subject Headings (MeSH)).* It contains over 250,000 concepts named by 590,000 biomedical terms, and reflects all names, meanings, and hierarchical and inter-term relationships that are present in the original source vocabularies. In addition, it establishes new relationships between terms from different source vocabularies [20].

Significant advances beyond the capabilities of existing database search systems might follow from fundamental improvements in the indexing of relationships. Existing index languages and subject heading systems (such as *MeSH*) reflect context-independent language structures, particularly synonymous and hierarchical relationships. These systems are not designed or intended to represent adequately the relationships between different subject headings that are appropriate for a particular article to which the headings are applied (hence are context-dependent) but not appropriate for all articles and contexts. For example, an article discussing arteriosclerosis as a possible cause of hypertension would be indexed under the subject headings "arteriosclerosis" and "hypertension"; there is no provision for linking the two terms together, in the process of indexing a given article, to show that a cause-effect relationship between them is discussed in that article. The hierarchical relationship between "arteriosclerosis" and "coronary disease", on the other hand, is valid in all contexts and hence is built into the MeSH structure itself. The requirement for improved indexing of context-dependent relationships calls attention to these relationships themselves as entities that merit more systematic study [9, 10], and has led to important research on interactive frame-based or

knowledge-based indexing [9, 10, 14, 15].

5.3. Comments on methodology

Any two literatures or sets of titles that share a common language will have many words in common irrespective of whether the two literatures have substantial or interesting scientific linkage. Hence we must address the question of whether ARROWSMITH, in manipulating title words, really helps reveal linkage of scientific interest. The A-list consists of words that co-occur in titles with other words (the B-terms) that co-occur in titles with C-terms. The list is subjected to three filtering processes -- an extensive stoplist, a probabilistic cutoff that retains only words strongly correlated (A with B and B with C) and a category restriction. Our results at least suggest that the more important and better-established A-B and B-C biological connections tend to pass through the filters. Even though the problem of finding nuggets of value among a large number of uninteresting connections persists, the above process of enrichment appears sufficient to permit the more interesting or important connections to be spotted easily by an expert. It is also our strong impression that the high-ranking biologically-plausible A-terms lead to a more extensive and much richer B-LIST and title display in *Procedure II* than do words of equal *a priori* plausibility but which are of low rank or not on the A-list at all.

We have defined the complementarity of two literatures based on the scientific arguments and discourse within those literatures, not on just shared language use. To examine and illustrate this distinction further, we developed a new A-candidate list (Figure 3), for the literature on Alzheimer's disease (AD), using a restriction category based on toxins or poisons [36], and analyzed the underlying biologic connections associated with one high-rank candidate, lead.

The appearance of the poisonous metal "lead" among the top-ranked words on the A-list for AD invites attention. Lead is well known as an environmental hazard with neurotoxic effects. Among the various high-ranking terms on the A-list that would seem worth investigating (including ozone, ethanol, TNF (tumor necrosis factor), IL (interleukin), cadmium) lead is a conspicuous and biologically-plausible choice. Even though all A-words participate in A-B-C *word* linkages, these linkages are not equally plausible for AD. For example, the A-B linkages for ozone tend to affect the lungs but

those for lead tend to affect the brain. Thus lead is judged to be a more promising candidate.

But it should not be surprising that the quite large literatures on lead and AD share a great deal of common language, including B-terms in titles, irrespective of whether lead and AD have meaningful biologic interaction. To pursue this question further, we examined not only the title linkages, but the underlying literatures as well. Specifically, 5 groups of effects could be identified in the separate literatures on lead and AD: i) Lead treatment or lead exposure alters cholinergic function in a number of systems; deficient cholinergic function is a hallmark of AD. Lead exposure was reported to cause a decrease in choline acetyltransferase in the septum, a brain area known to be particularly deficient in this enzyme in AD patients. ii) Lead has effects on calcium-dependent signal transduction pathways involving adenylate cyclase, calmodulin, and kinase; all three signal transduction pathways are reported to be abnormal in AD and are thought to participate in its pathogenesis. iii) It is well established that lead affects brain vasculature and glial cells, and alters the blood-brain barrier; these are also reported to be abnormal in AD. iv) Lead exposure is associated with oxidative stress that generates free radicals (see 4.2); many reports have indicated that excess free radical formation occurs in AD. v) Lead exposure interferes with long-term potentiation in the hippocampus, a cellular model of short-term memory; the latter is known to be abnormal in AD.

The connections that were found appear to go far beyond the matter of "just" shared language, and indeed suggest that the cellular effects of lead exposure entail functional deficits that also accompany AD. We cannot conclude on that basis that lead exposure is necessarily a significant risk factor in AD, for this inference would require direct evaluation of lead in living systems. But the foregoing argument does tend to support our claim that the A-list for Alzheimer's disease identified agents having meaningful A-B-C linkages with the source literature.

6. Application to other fields and disciplines

The question has often been raised of whether our techniques can be applied to fields other than biology and medicine. In principle it is possible, but in practice the answer may depend on the accuracy and specificity of article titles; in biology and medicine, titles tend to be highly specific and informative. The same techniques could be applied

of course to abstracts, but we haven't tried it and do not know whether the advantages of establishing more connections will be outweighed by the disadvantages of more "noise" in the system. Moreover, all of the examples we have worked on so far have been in the subset of biomedical literature that is relevant to mammalian physiology. In this corner of the "real world", everything is richly interconnected. Thus each publication about some aspect of that world is likely to create an intricate web of implicit and unintended connections within the corresponding world of recorded knowledge. Fields that are not as intimately interconnected may be less rewarding for our methods. In the field of chemistry, our A-B-C model could refer to a chemical reaction pathway and would have in that case interesting similarities and contrasts to work in AI on the automatic generation of reaction pathways [38].

7. Conclusions and implications

Bringing together two complementary but noninteractive literatures from different specialized areas of research can reveal undiscovered public knowledge — unnoticed implicit relationships not apparent in the two literatures considered separately. This paper has described an experimental "discovery support system"[8] called ARROWSMITH which embodies a replicable database search procedure and related software that produces heuristic aids to finding complementary literatures and to deriving novel scientific hypotheses. Applying ARROWSMITH has led to testable hypotheses, several of which have been experimentally corroborated, that demonstrate the effectiveness and value of the system.

ARROWSMITH, operating in an environment characterized by the unruly problems of natural language text and the immensity of the scientific record, is a practical system that seeks immediate results in furthering the aims of biomedical research. At the same time, it is a research tool for studying undesigned but human-created structures in the literature of science. Each use of the system creates numerous examples of word-linked titles suggestive of complementarity that are of potential value in examining the logic of scientific discourse, in new approaches to the indexing of relationships [9, 10, 14, 15], and as a source of ideas for modelling the process of discovery. Literature-based discoveries may also open new lines of investigation in the growth of knowledge and the drives toward specialization and fragmentation in science [18, 19, 39, 41, 42]. We invite

inquiries from those who might wish to try using the system on problems of their own.

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FOOTNOTE -- page 1

1

A, B, and C refer either to physiological conditions or agents or to the search terms based on them, or to the literatures that result from the search, the context indicating which meaning is intended. "B" may also stand, generically, for Bi with i=1,2,3,..., as in Figure 1.

FIGURE CAPTIONS

Figure 1

A Venn diagram that represents sets of articles, or "literatures", A and C, that have no articles in common, but which are linked through intermediate literatures, Bi (i=1, 2..). Such a structure may contain unnoticed useful information that can be inferrred by combining pairs of intersections ABi and BiC.

Figure 2

A schematic diagram of title-word pathways that, proceeding from right to left, lead from a source literature C through intermediate title- words (B-terms) or literatures, to one or more title words that can represent promising target literatures, Ai (i=1, 2, ...). A ranking algorithm for each Ai, based on the total number of B-pathways that lead to it, is illustrated. The rank numbers (number of paths) are shown in the leftmost column.

Figure 3

Top twenty (approx.) entries on the A-candidate lists for migraine, Raynaud's disease, and Alzheimer's disease, produced by *Procedure I* (Figure 3). The ranking numbers shown in the first column represent the number of title-word pathways connecting A to C, and were generated automatically by the process illustrated in Figure 2. Not shown, but included in the actual output, are the B-terms (illustrated in Fig. 2) that contribute to the rank score.

Figure 4

A schematic flowchart of *Procedure II*. The procedure begins with a downloading of titles from literatures A and C, and proceeds to the lower right where an output display is produced as a heuristic aid for the human user of the system. The display is organized to facilitate comparison of A-titles with C-titles for each B-term that they have in common, and serves as a guide to the literature.

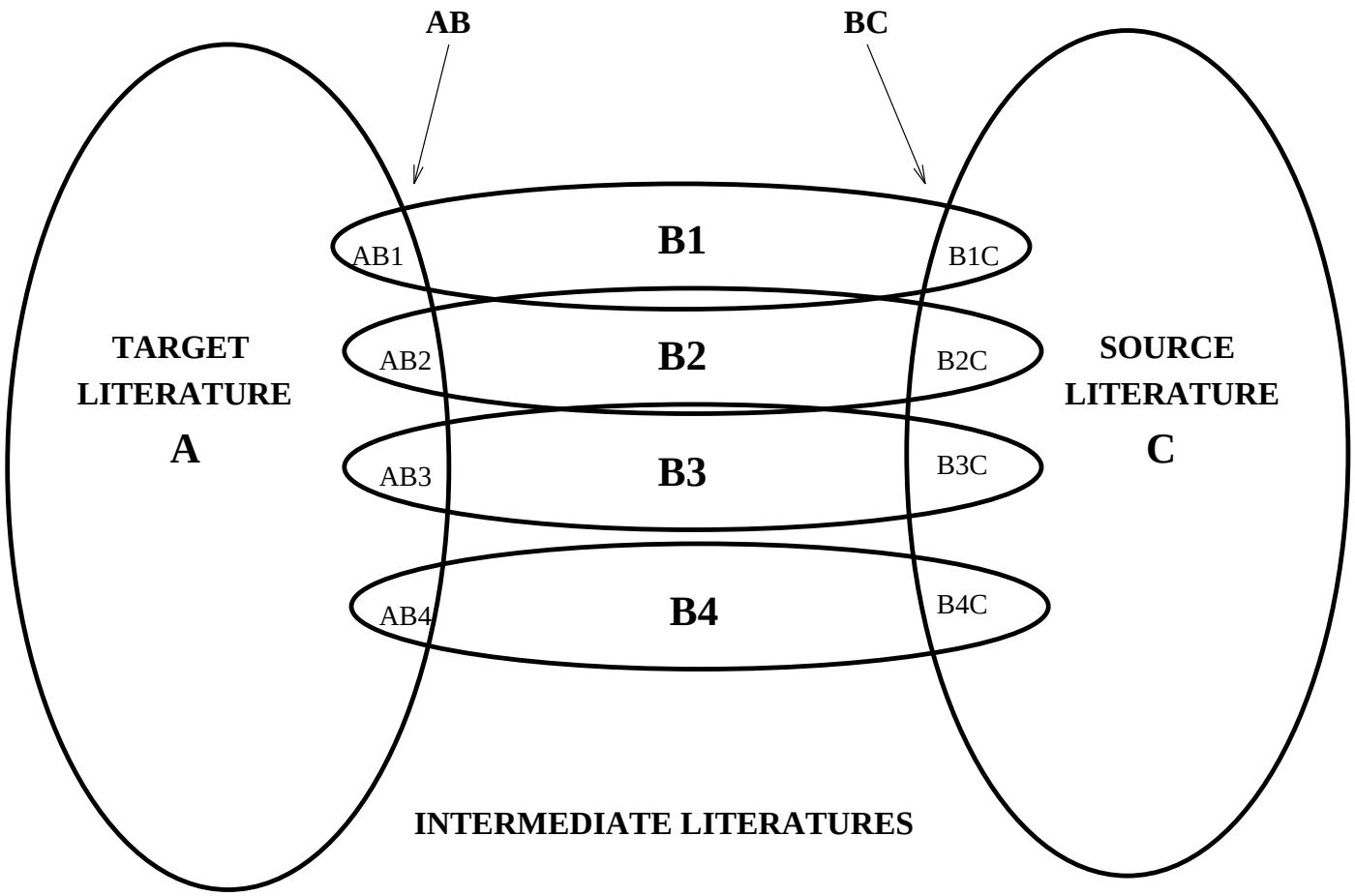
Figure 5

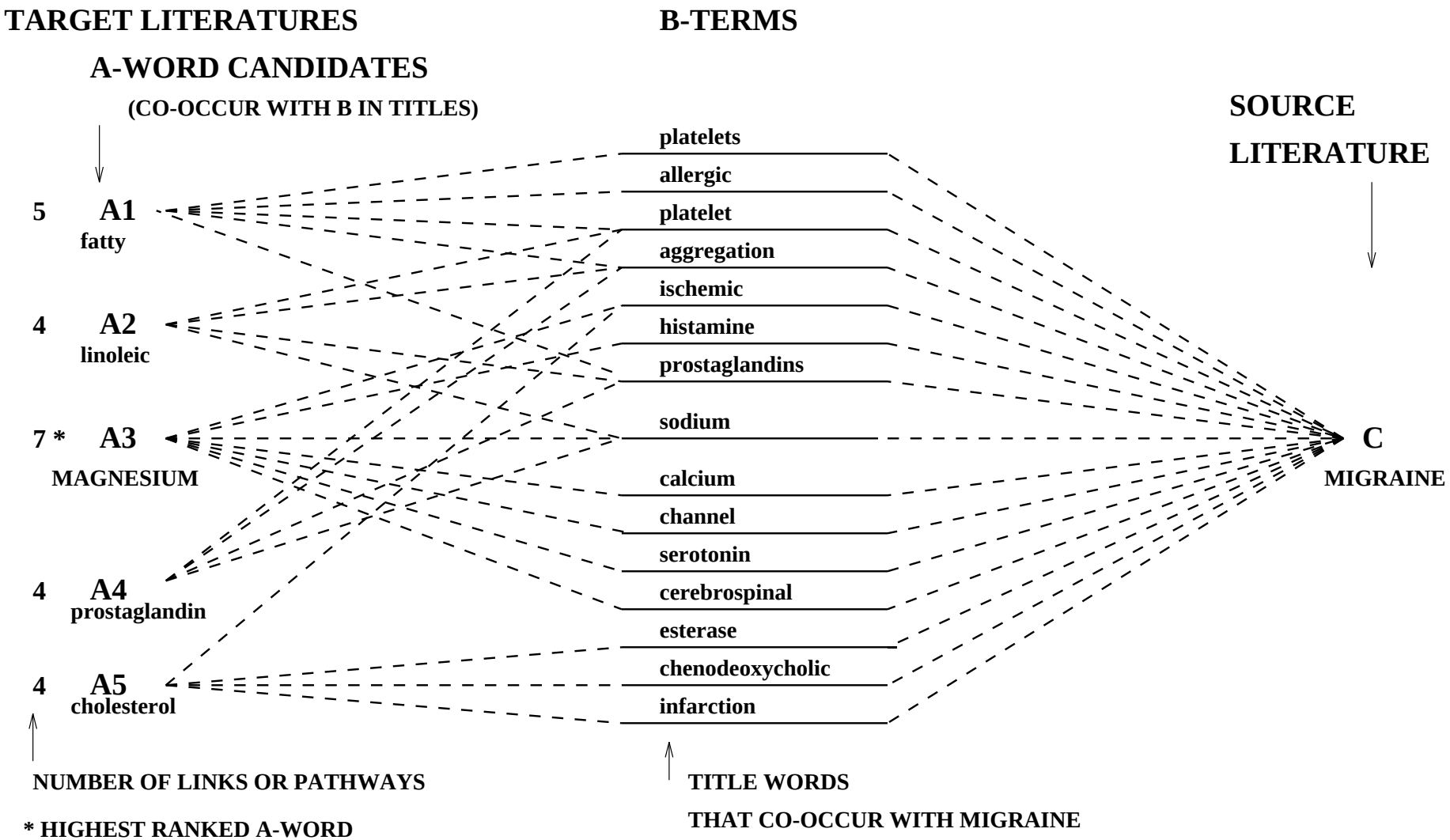
Selected entries from a printed display of the *Procedure II* output for two sets of titles that contain the word "magnesium" (A-left column) or "migraine" (C-right column), respectively. The headings shown are B-terms (in alphabetic sequence). Under each B-

term are titles containing that term in the two columns of the display. This arrangement facilitates comparing "magnesium" titles with "migraine" titles for each B-term that they have in common. Shown here are examples of B-terms in which biologically meaningful relationships A⇒B and B⇒C are suggested by the titles; citations to the literature are also identified. Although, for each B-term, only a few titles are shown, in general there may be as many as several hundred. To avoid excessive output, a limit to the number of titles displayed for any one B-term can be set interactively by the user.

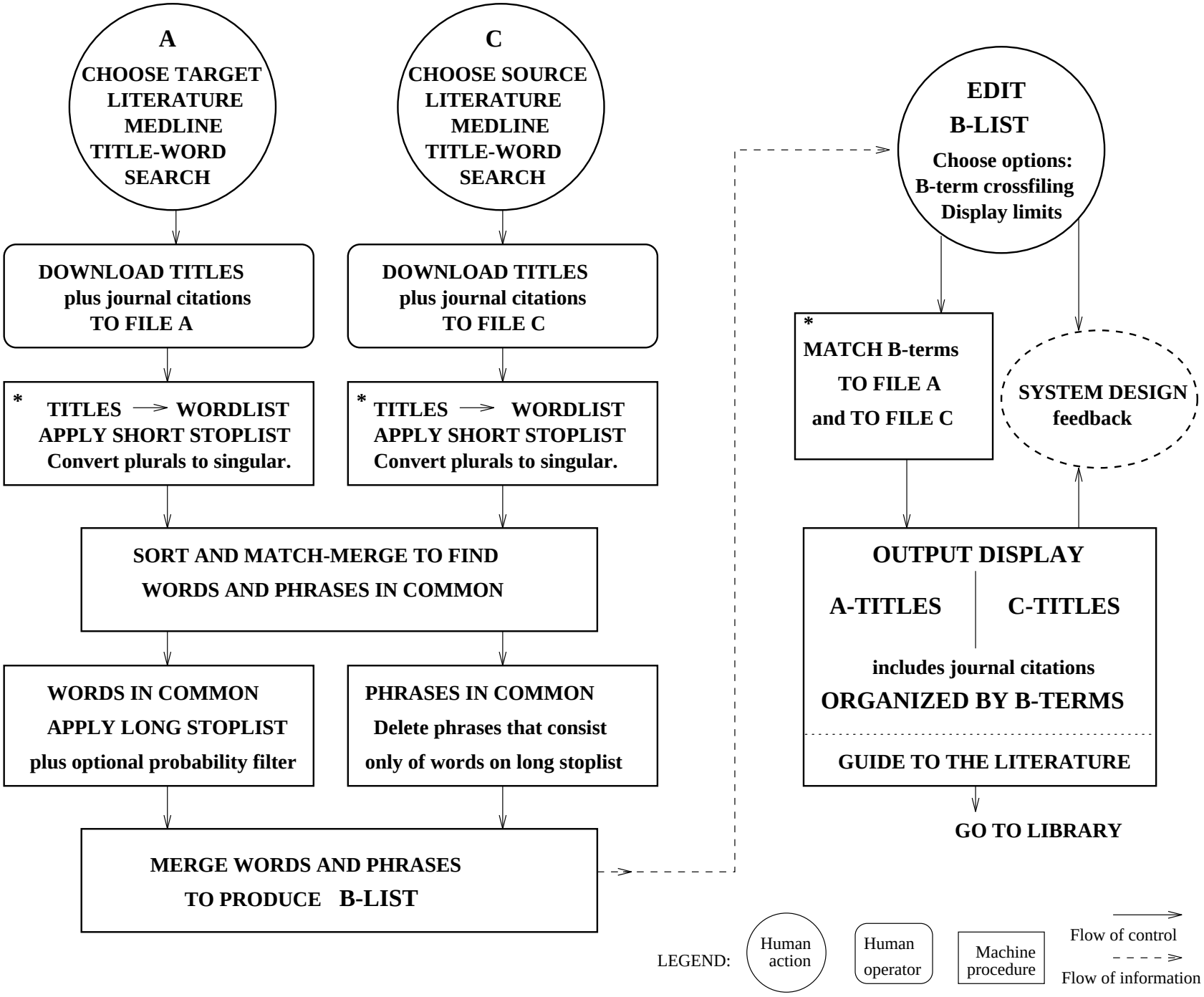
Figure 6

Selected entries from the B-LIST for magnesium and migraine, and for fish-oil and Raynaud's disease, produced by *Procedure II* (Figure 6). The two numbers shown in the two columns to the left of each word list represent the number of articles within the BC and AB intersections, respectively, as illustrated in Figure 1. The asterisks mark entries identified in the original studies [21, 23].


AB
BC
B1
AB1
B1C
B2
AB2
B2C
B3
AB3
B3C
B4
AB4
B4C
TARGET
LITERATURE
A
SOURCE
LITERATURE
C
INTERMEDIATE LITERATURES


TARGET LITERATURES
A-WORD CANDIDATES
(CO-OCCUR WITH B IN TITLES)
B-TERMS
SOURCE
LITERATURE
5 A1
fatty
4 A2
linoleic
7 * A3
MAGNESIUM
4 A4
prostaglandin
4 A5
cholesterol
platelets
allergic
platelet
aggregation
ischemic
histamine
prostaglandins
sodium
calcium
channel
serotonin
cerebrospinal
esterase
chenodeoxycholic
infarction
C
MIGRAINE
NUMBER OF LINKS OR PATHWAYS
* HIGHEST RANKED A-WORD
TITLE WORDS
THAT CO-OCCUR WITH MIGRAINE

MIGRAINE	RAYNAUD’S DISEASE	ALZHEIMER’S DISEASE
7 magnesium	6 fatty	17 endotoxin
6 hormone	5 vitamin	13 toxin
6 b	4 sodium	13 methyl
5 salt	4 prostaglandins	13 d
5 pyridoxine	4 oil	12 lead
5 pressure	4 iga	12 ethanol
5 lipids	4 c	11 ozone
5 lipid	4 a2	11 necrosis
5 hypertension	4 5	9 neurotoxicity
5 hepatic	3 renin	9 calcium
5 fatty	3 polyunsaturated	9 c
5 e	3 platelets	8 seizures
5 d	3 magnesium	8 pertussis
5 cholesterol	3 lipid	8 mptp
4 vitamin	3 linoleic	8 hepatic
4 renin	3 glutathione	8 dna
4 prostaglandin	3 choline	7 tnf
4 methionine	3 angiotensin	7 il
4 membrane	3 anemia	7 b
4 linoleic		6 cadmium
4 folate		
4 c		
3 thiamine		
3 potassium		


A
CHOOSE TARGET LITERATURE MEDLINE TITLE-WORD SEARCH
C
CHOOSE SOURCE LITERATURE MEDLINE TITLE-WORD SEARCH
EDIT B-LIST
Choose options:
B-term crossfiling
Display limits
DOWNLOAD TITLES plus journal citations TO FILE A
DOWNLOAD TITLES plus journal citations TO FILE C
* MATCH B-terms TO FILE A and TO FILE C
SYSTEM DESIGN feedback
* TITLES → WORDLIST
APPLY SHORT STOPLIST
Convert plurals to singular.
* TITLES → WORDLIST
APPLY SHORT STOPLIST
Convert plurals to singular.
SORT AND MATCH-MERGE TO FIND WORDS AND PHRASES IN COMMON
OUTPUT DISPLAY
A-TITLES
C-TITLES
includes journal citations
ORGANIZED BY B-TERMS
GUIDE TO THE LITERATURE
GO TO LIBRARY
WORDS IN COMMON
APPLY LONG STOPLIST
plus optional probability filter
PHRASES IN COMMON
Delete phrases that consist only of words on long stoplist
MERGE WORDS AND PHRASES TO PRODUCE B-LIST
LEGEND:
Human action
Human operator
Machine procedure
Flow of control
Flow of information

MAGNESIUM - A

CALCIUM CHANNEL
87272894
Mg2+-Ca2+ interaction in contractility of vascular smooth muscle: Mg2+ versus organic calcium channel blockers on myogenic tone and agonist-induced responsiveness of blood vessels. [Review] Can J Physiol Pharmacol. 65(4):729-45, 1987
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EPILEPSY
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EPILEPTIC
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Epileptic-type convulsions and magnesium deficiency. Aviat Space Environ Med. 50(7):734-5, 1979
78106635
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HISTAMINE
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ISCHEMIA
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Mild hypothermia and Mg++ protect against irreversible damage during CNS ischemia. Stroke. 15(4):695-98, 1984
85097212
Pharmacologic inhibition of cerebral vasospasm in ischemia, hallucinogen ingestion, and hypomagnesemia: barbiturates, calcium antagonists, and magnesium. Am J Emerg Med. 1(2):180-90, 1983

ISCHEMIC
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The ionic basis of the anti-ischemic and anti-arrhythmic properties of magnesium in the heart. [Review] J Am Coll Nutr. 6(1):27-33, 1987
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MIGRAINE - C

CALCIUM CHANNEL
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Migraine treatment with calcium channel blockers. [Review] Acta Pharmacol Toxicol (Copenh). 58 Suppl 2:161-7, 1986.
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EPILEPSY
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Migraine-epilepsy relationships. [Review] Epilepsy Res. 1(4):213-26, 1987
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Is there a common pharmacological link between migraine and epilepsy? [Review] Funct Neurol. 1(4):515-20, 1986
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HISTAMINE
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ISCHEMIC
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The ischemic hypotheses of migraine. Arch Neurol. 44(3):321-2, 1987
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Migrainous ischemic optic neuropathy. Neurol 35(1):112-4, 1985
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Migraine, a risk factor for ischemic cerebral stroke. Med Welt. 34(8):233-4, 1983

MAGNESIUM - A

PROSTAGLANDIN
80235079
Magnesium ions control prostaglandin reactivity of venous smooth muscle from spontaneously hypertensive rats.
Prostaglandins Med. 4(4):255-61, 1980
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SEROTONIN
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SPREADING DEPRESSION
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VASOSPASM
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Pharmacologic inhibition of cerebral vasospasm in ischemia, hallucinogen ingestion, and hypomagnesemia: barbiturates, calcium antagonists, and magnesium. Am J Emerg Med. 1(2):180-90, 1983
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Withdrawal of magnesium causes vasospasm while elevated magnesium produces relaxation of tone in cerebral arteries.
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MIGRAINE - C

PROSTAGLANDIN
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MIGRAINE-MAGNESIUM B-LIST
(selected)

BC	AB	B-term	
5	3	amine	
3	2	anticonvulsant	
5	2	calcium antagonist	*
10	2	calcium channel	*
4	1	calcium entry	*
5	3	catecholamine	
5	8	diabetes	
3	3	dopamine	
14	2	epilepsy	*
5	6	epileptic	*
11	11	hemodynamic	
14	13	histamine	
11	3	ht	*
15	4	hydroxytryptamine	*
3	11	hypertension	
3	2	hypoxia	*
6	3	immunoglobulin	
3	7	inflammatory	*
2	0	ischaemia	
12	3	ischemia	
6	1	ischemic	
9	8	muscle contraction	
5	4	olfactory	
14	5	oral contraceptive	
10	3	paroxysmal	
14	5	platelet aggregation	*
4	2	progesterone	
14	4	prolactin	
10	3	prolapse	
12	5	prostaglandin	*
8	3	reactivity	*
16	7	relaxation	
10	7	reserpine	
8	14	seizure	*
11	5	serotonin	*
4	4	spasm	*
5	2	spreading depression	*
7	5	stress	*
6	7	tryptophan	
4	5	vasospasm	*
6	4	verapamil	*

RAYNAUD-FISHOIL B-LIST

BC	AB	B-term	
1	1	angina	
2	2	arthritis	
2	5	blood pressure	
10	5	blood viscosity	*
6	7	calcium	
12	1	capillary	
2	1	collagen	
4	2	deformability	*
1	5	diabetic	
3	1	fibrinolytic	
1	1	hemolytic uremic syndrome	
9	2	hypertension	
1	4	hypertensive	
1	1	iga	
3	3	infarction	
1	3	inhibition platelet	*
1	5	ischemic	
8	2	lupus	
1	1	mediterranean	
2	1	pgi2	
2	13	platelet aggregation	*
3	14	platelet function	*
1	1	polymorphonuclear	
10	9	prostacyclin	
10	25	prostaglandin	*
2	1	prostaglandin i2	
1	1	reactivity	*
1	1	serotonin	*
1	2	thrombotic	
6	11	thromboxane	*
1	2	thyroid	