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ABSTRACT

The computer program which performs spatial reconstruction of events photographed in a bubble chamber is required to eliminate human and digitizer errors. It recongnizes and corrects for single nuclear scatterings in the presence of multiple Coulomb scatterings; these, if left undetected, would lead to false estimates of the momenta and angles of tracks. Momentum components are determined and kinematic constraints are applied. Measured parameters are transformed into special reference frames, and quantities of physical interest are calculated. Results are stored in a tape file containing all events of one reaction type. Data are obtained as page output for each event and CRT displays of selected parameter distributions for all events.

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A bubble chamber is used in high-energy physics as a detector of charged particles in which quantitative measurements may be performed. The medium in the chamber is heated under pressure; this is suddenly released a few milliseconds before a beam of particles from an accelerator is passed through the chamber. A charged particle generates a line of nuclei for boiling, corresponding to the path of the particle. The track of bubbles is photographed a few milliseconds later, with two or more lenses so that the spatial position can be calculated.

Generally, a magnetic field is present in the chamber to cause the charged particles to move in helical arcs. Each arc has a radius proportional to the momentum of the particle and a sign of curvature that indicates the sign of charge of the particle.

The bubble density along the track is a function of the particle's velocity. From this and the momentum the mass of the particle can be calculated. This yields a determinate solution only at low energies, but is the most useful means of identifying the particle at these energies.

The problem facing the physicist, therefore, is threefold; to identify the charged particles in the picture and from these identities to infer the reaction that took place; to get the best estimate of the energy and momentum

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parameters for each of the particles participating in the reactions, including neutral particles which are not seen nor measured; and to transform the measured quantities into parameters useful for analyzing the properties of each reaction. This procedure must be repeated for each event found in the experiment. In current physics typical numbers of events to be analyzed range from a few hundred to tens of thousands.

We associate the word "event" with a single nuclear reaction and the word "chain" with two or more events related by connecting particles, whether charged or neutral. Calculations for each of these events amount to about 30 seconds of scientific computation on an IBM 709. The computer program must be capable of organizing the computations to fit the wide diversity of configurations represented by the data. With so many events in his experiment, the physicist finds it necessary to rely upon the computer to file, retrieve, and summarize his data.

The goal of our programs is to provide capabilities indicated as follows. A typical year's research will include four 20,000-event and ten 2,000-event experiments. Each will have five different topological configurations, each of which must be treated by a different calculational process. For quality control and to guide the course of the experiment, it will be necessary to summarize the data at ten intermediate steps as well as make the final summarization.

We have divided the problem into the following phases: scanning, in which each picture is looked at to find events important to the experiment; measuring; track calculation, in which measurements are reduced to the basic angle and momentum parameters independent of the particular nuclear reaction hypothesized for the event; event calculations, in which the kinematical properties of the event are used in an attempt to identify which particular reaction occurred and to improve the basic measurements by imposition of constraints; experiment summarization and statistical analysis of all events of each reaction. A representative event is shown in Fig. 1.

There are three classes of input to the computer. (See Fig. 2.) One is composed of data from the scanning operation. During the scan, tallies are kept of events that need not be measured but are valuable in estimating the background and contamination of the reaction process being investigated; also, codes describing the mass or masses to be used for each track and class labels to identify the event with one or more particular reaction types are included in this input. A second class of input, which is generated during the experimental run by automatic digitizing equipment, contains data useful in estimating the total number of particles in the chamber and parameters needed to evaluate some of the measurements. The third class of input data is the set of measurements of points lying along the tracks.

Each charged track is measured by recording the x, y position on the film of points on the track in each of the stereoscopic views. Approximately 20 points are measured in each view and normally three views are measured. In addition to the points along the tracks, three fiducials are measured in each view to orient the track in the chamber. The measuring-microscope operator also inserts information that correlates measurement with the film library. Digitized projection microscopes having track-following ability are used to make the measurements. One event is measured in 10 minutes; thus, three of these measuring devices operating continuously can measure our 100,000 events in the year.

We use rotary-shaft position digitizers to measure to 1 μ on the film. A read-out consists of two five-digit numbers characterizing the x and y positions of the point on the film. Our experience is that one read-out in 500 contains a digitizer error. Fortunately, because of the construction of the digitizer units, the errors are most likely to occur in the most significant two digits, and therefore are fairly easily detected.

Shortly after the data are input to the computer they are checked by requiring that they represent locally smooth measurements taken in one direction along the track. Multiple scattering, turbulence, and other distortions do not cause large local deviations from smoothness. Therefore we use a four-point Lagrangian interpolation on consecutive points, and require that the measured point lie within approximately one track width of the computed position for that point. Each point in turn is checked. If a point is found that does not meet the tolerance, it is deleted and the process continues. No more than one of eight consecutive points may be deleted without causing the measurement to be rejected.

Processing occurs some time after the measurement is made. It is our practice to measure and stockpile events of one experiment in order to have a large volume to process at each pass. The first program to receive the data scans for format and content errors. Some categories of error--for instance, digitizer errors--can often be corrected without biasing the data. Other categories, such as the failure to measure one track or a digitizer error occurring in one of the fiducial measurements, are catastrophic and require remeasurement. In this case, a card is punched containing identification of the event and a description of the error found. This information is also recorded on the library tape so that events that consistently fail may be sent back to the physicist for further scanning analysis.

Some filtering is done at this stage. In heavy media like propane, one in five tracks is made by a particle that elastically scatters about the carbon nucleus. Because momentum transferred is usally fairly small, this has the appearance of a kink in the track. The scattering is of no great physical interest but its presence, if ignored, would seriously bias the calculated momentum. The program, therefore, accepts flags in the measurements indicating a kink and segments the least-squares fitting of interpolation curves of the kinks. On the other hand, it is usually undesirable to attempt to signal these in the measurement. The program may be allowed to search the input data for kinks and to set its own flags. The procedure is to use the data known not to contain digitizer mistakes, and to perform a second Lagrangian interpolation, this time using every third point in order to get a longer characteristic length. A residual, equal to the distance of the measured point from the interpolated value, is calculated for each point. The average of these residuals is found and each value is compared with four times the average. Points having departures greater than this are considered to be kinks.

In each view third-order optical theory is used to correct the large pincushion distortion introduced by the glass and oil in the pressure vessel. The correction is made by calculating the position x', y' that would have been measured if the point x, y had been photographed in air.

The corrected points now obey conical projection geometry. When three views are measured it is possible to combine them into two pairs yielding satisfactory stereo. Points in one view corresponding to those measured in the other view are found by local interpolation, and are combined to provide spatial reconstruction. By this reconstruction for two pairs of views, two partially independent sets of results are obtained and may be compared to detect gross errors.

The spatial points are now fitted by a least-squares process to an interpolation curve. The points are projected into a plane normal to the magnetic field at the center of the track. In this projection a chord drawn from the first to the last points is defined as the x axis. A curve of the form

$$y = Ax^2 + Bx + C$$

is fitted by least squares. The curvature is used to calculate the mass-independent momentum parameter at the center of the track. The space points are next projected into the plane containing the direction of the magnetic field and the x axis. Since the magnetic field is assumed to everywhere lie in this plane, the points in this projection are fitted by least squares to the line

$$Z = Dx + E.$$

From these least-squares coefficients the directions of the momentum vectors at the vertex and at the end of the track are calculated. The direction of a momentum vector is expressed in terms of the spherical coordinates α and β, where α is the colatitude and β is the longitude. The length of the track is calculated as the length of the interpolation-curve arc. An estimate of the weight of the coefficients is made and used to determine what are called internal errors on the direction and momentum.

An output tape is prepared which contains several binary records for each vertex. Since the number of tracks per vertex may range from 1 to 20 we find it convenient to form tape records for each track. There is a separate identification record as well as a record for each set of scanning or assignment-request data.

This output tape is a library of all information pertaining to events of this experimental run: on it we collect scanning information, the parameters (produced during the experimental run) describing chamber operation, measures and reduced measures of the events, mass codes, and comments made by the physicists. If a measurement or calculation error is discovered for an event, an error record describing it is recorded on the library for later statistical use. Each program reads this library tape as input and produces an updated version of the tape as output.

The order of the library is the order of the film containing the events; thus, this library is a digital abstraction of all data describing the events of interest. One reason for having such a library is that we often accumulate a sizeable backlog of data between the experimental runs producing the film and the scanning, and between the scanning and the measuring. Allowing the computer to collate and store the separate data until all arrive is one convenience of a tape library. Another advantage is that it is possible to perform experiments on the measured data as described on the tape library; thus, many questions that subsequently arise may be answered without manual effort by making new calculations or summarizations upon this tape library. The program prepares reports describing the condition of the digitizers and the statistical occurrence of measuring errors as a function of measurer, digitizer position, and experiment. Approximately 1,000 events are on each reel of tape; therefore, libraries range from one to more than 20 reels for each "generation."

It should be noted that the calculations thus far performed have been independent of any assumptions of particular nuclear reactions. These calculations are merely a reduction of the film measurements. All subsequent calculations introduce additional assumptions concerning the nature of the nuclear reaction represented by the tracks in the chamber.

There may be many thousand events on the general FOG library. We have assumed that only a fifth of the events would be calculated in one mode. Because this smaller sample represents a homogeneous topological form in the chamber, it is convenient to abstract from the general library and to place on a specific library a portion of the data, namely, the identification and the reduced form of the measurements together with the scanning data and the mass codes appropriate for this class. The selection may be made in several ways. One is preassignment, in that mass codes and assignment designations may be entered as input data specifically for each event. This is particularly appropriate if there are only a few events and if each of the events differs in small details from its cohabitors of the specific library. Another means by which events may be selected is the application of selection criteria to the data on the FOG library by a CLOUDY kinematics program. We have a program which routinely looks at the FOG tapes and searches for events meeting criteria specified by the physicists. These criteria may be ranges of values of the parameters describing the data or specification of certain topological classes of events. This technique is particularly appropriate for the larger classes of data and for the somewhat simpler event structures.

The selected data form a tape library of events that are at least not inconsistent with a particular reaction. For each track there is a mass code corresponding to either one or several possible mass identifications for that track. The program sets up a complete set of mass permutations subject to rules of strangeness, charge conservatory and baryon conservation. These limit the permutations to physically meaningful ones. These rules can be changed or omitted as the experiment requires.

Each set of mass permutations, and therefore each specific nuclear interaction, is now organized as a chain on the CLOUDY library. A particular mass is assumed for each particle, therefore the mass-dependent momentum at the vertex may be calculated. The precision of measurement may be estimated for the angles and the momentum as a function of the configuration of the track in the chamber, the mass of the particle, and its momentum. These estimates we call external errors. For its future use the program takes the larger of these or the least-squares internal errors as characterizing the measurement precision. Frequently one is dealing with fairly small numbers of events so that it is not possible to look at distributions of parameters and estimate the population variance with any degree of accuracy. The technique of kinematic constraints requires that the variance of each measure be known beforehand. Therefore external errors are normalized to all previous data obtained with the chamber.

At each interaction vertex momentum and energy must be conserved. There are four constraints--three momentum and one energy--that may be applied at the vertex in order to test the assumed identities and to produce an improvement of the data if the assumptions are correct. Two-body final-state reactions in which a moving particle strikes a target at rest in the laboratory frame of reference and produces two outgoing tracks have the following constraints: conservation of momentum in the direction of the incoming particle; conservation of transverse momentum in the plane of the three tracks; coplanarity of the three tracks; and conservation of total energy. Notice that the coplanarity constraint does not involve momentum but only the usually well-measured angles.

When chains of two or more vertices are measured, it is possible to apply these constraints at each vertex as well as to constrain the connecting track. There are three constraints for each connecting track affecting momentum and the two space angles. By application of constraints, missing or poorly measured variables can be synthesized. Thus, if one outgoing track is neutral, it still is possible to apply one constraint in addition to using the other constraining equations to supply the three missing variables.

Certain nonanalytic constraints are also introduced. In the constraining process there is nothing to prevent a momentum from becoming negative. However, a finite length of charged track sets a lower bound on the momentum. The constraining process may also yield the colatitude as negative or greater than π; i.e., unphysical. Events are not physically meaningful if their constrained version violates such conditions; therefore at each iteration of the constraint these values are arbitrarily set back to the extrema of the physical region.

The technique of constraints is attributed to Gauss and is developed in Deming, Statistical Adjustment of Data (John Wiley and Sons, Inc., New York, 1943). It was first suggested for bubble chambers by Horace Taft of Yale. The two-body kinematical constraint process is represented in Fig. 3. In this the x_i represent true or best values of the measured parameters. The x_i^m represent the measured value, and the u_i represent population variances for the parameters. The α's are Lagrangian multipliers and the F's are the constraining functions.

The technique is to assume that the **F** functions are linear in x_i and to solve for the value that minimizes M. Since the F's are, in fact, highly nonlinear, one calculates the partial derivatives of the F's with respect to the x_i's for the best value of x, and assumes this constant over values in the neighborhood of the point calculated. In practice one approaches the solution for the minimum value of M by iteration. At the minimum the F's are identically zero and therefore M is a χ^2 test of goodness of fit to the assumptions.

Following the constraint procedure there is a new set of values for the measured parameters. The interpretation of these data usually requires that numerical transformations be made to produce derived quantities useful for comparing with theory. Such derived quantities include center-of-mass transformations in which the momentum vectors and energies are described in terms of a frame not at rest in the laboratory system. For studies of polarization and parity, one frequently wants the momentum vectors to be referred to preferred planes determined by the event. This is done by spherical-coordinate rotation, and frequently the product of a number of coordinate rotations is required to produce the desired parameter.

The chains on individual CLOUDY libraries are homogenous to the degree that each may represent the sought-after nuclear reaction; however, the number of tracks in each vertex and the number of vertices in the chain may differ from chain to chain. The programs are self-organizing to deal with these complications. The differences do not matter to the FOG program, and the CLOUDY program is able to omit portions of calculations requested in general for the events when specific chains do not have the requisite data measured. The same program must deal with all different types of events in the form of different CLOUDY libraries. To do this we define different modes of operation for the programs.

Because many of the chamber parameters change from one experiment to the next and because different sets of assumptions are included in the calculations of different experiments, the program must adapt itself to the requirements of a particular library before beginning calculations. This is done by having constants and key words that identify assumptions for each of the experimental libraries written separately on the SYSTEM tape.

Because the calculational procedure differs for practically every experiment library, the actual organization of the CLOUDY program is in the form of many arithmetic and editing subroutines controlled by a short logical section defining a particular mode of operation of the program.

After the kinematic calculations have been completed there exists on the CLOUDY library tape a detailed numerical description of each chain. The FAIR output program is now able to produce a complete and edited numerical description of the chain. The output program marks the CLOUDY library tape to indicate which events have been listed and which have not, so that subsequent reading of the library will not normally repeat previous output.

The FAIR program abstracts from the CLOUDY library according to criteria that describe which events are to be included. These selection criteria are introduced into the program at execution time. In general they are a set of logical AND/OR operations upon any of the kinematical or identification parameters related to the chain. During FAIR program execution the selection criteria are combined to form tests for inclusion of data; then the library is read and chains meeting these tests are either abstracted for later statistical use or are immediately edited into page output and written onto the SYSTEM output tape. During any one pass there may be as many as five sets of selection criteria used for the same CLOUDY library. This limit is determined by the number of available tapes.

The page output program is controlled by this same selection criterion. In the large experiments it is not practical to read the page output for each chain; therefore those chains which are within the regions of parameter space expected by the physicist may be suppressed and only the anomalous pages listed. This is perhaps a ten-to-one reduction in the amount of data and gives the physicist a chance to concentrate on the apparently anomalous events.

At the conclusion of the CLOUDY library pass, requested page and card output will have been produced for chains meeting the selection criteria.

If summarization has been requested, there will be one or more tapes containing an abstraction from the CLOUDY library of data meeting the criteria. These tapes are rewound and each of them in turn is used as a source for the summarization pass. Each set of selection criteria has associated with it a list of parameters to be summarized. This list is interpreted item by item, and the summarization is executed by repeated passes of the abstract tape.

We are presently equipped to make histograms, weighted histograms, and two-parameter scatter diagrams as cathode-ray-tube displays. The program can also produce sorted lists in which the requested parameter is ordered by its value and then listed with each line containing the requested value in sort, the identification of the chain, and as many as three other parameters selected from the data. For the CRT plots, the second pass of the abstract tape displays the points of the scatter diagram and causes tallies to be accumulated for the histograms. At the conclusion of the second pass the shape of the histogram is displayed.

Because most of our production running is done by computing-center personnel who should not be required to assume responsibility for complicated decisions, we find it desirable to have a SYSTEM supervisor program to coordinate the processing of the data by the various programs. This is a rather limited supervisor, permanently occupying about 300 words in memory and performing the following functions: control of the clearing of memory and the loading of programs parts from a SYSTEM tape, assignment of the logical designation of tapes used as input and output for the programs, and control of the SYSTEM and PRINT tapes and of the online printer. The online printer is used for communications to the operator and to log the labels of tapes, the control card deck, results of operator decisions, and other information related to the processing; thus, the listing is a running journal of events significant to the processing. The card reader uses an input deck which is an intermixture of the SYSTEM control cards and other cards for specific programs. These two types are distinguished by the requirement that non-SYSTEM cards must have no punches in the 9-left row.

The SYSTEM program has a limited monitor that can be made to assume control of the machine should a program get into trouble. When the "Load Tape" button is pressed the monitor dumps the contents of cores onto the SYSTEM print tape, and relinquishes control to the normal supervisor program for execution of the next program. We find that this amount of supervision is useful, as operators can then run the program with a minimum of instruction. It also greatly assists the debugging, since, by using this combination, we can get three to five debug shots on different programs in one 5-minute run.

To facilitate checkout, sense-switch control is used to request additional dynamic memory dumps via the monitor at certain prespecified points written into the program. These are merely TSX transfers to the monitor, and stay in the program after it is debugged so that if for some reason a particular set of data causes trouble, it is possible to get the intermediate dumps merely by putting the sense switch down.

For the library operations we have developed a set of tape-handling subroutines which process the data of the libraries and remove the handling of the tapes from the list of things the programmer has to think about when he is writing a program. These subroutines check the redundancy triggers during READ and WRITE operations, check the transfer to cores by means of the ACL command, perform the buffering and tape-synchronizing operations, check the library end labels to make sure that the input and output tapes are mounted in the proper sequence, and keep statistics on the number of tape failures.

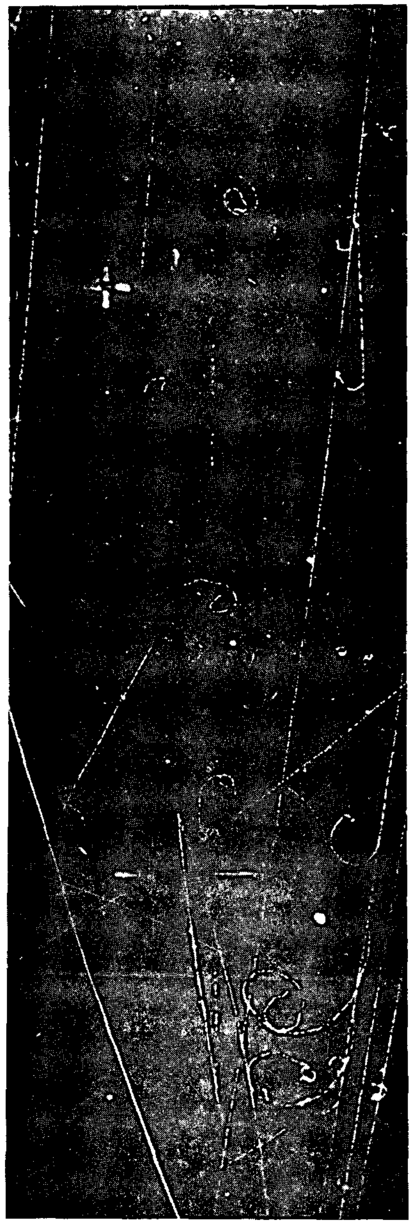
Each library has two logical tape units so that at any time one can be in use while the other is rewinding or available for mounting the next reel. The tape flip-flops are under control of the tape-handling subroutines. Our only problem has been overwriting on completed output tapes when the operator is careless about changing them promptly. A "Rewind-Unload" command has been requested to preclude this.

This system first came into operation in January of this year for **FOG** and in July for **CLOUDY** and **FAIR**. We have planned a number of extensions to these programs, both in the sense of extending the types of calculations that can be performed and in simplifying the form and content of the input.

In **FOG** our plans now include the following: improvement of initial trackfit approximations, extension of the geometric parameters describing the chamber so as to accommodate other bubble chambers, relaxing of the necessity for supplying track-number identification with the input, improvement of the input description of ionization, and introduction of an ability to deduce mass codes and event types more independently than now.

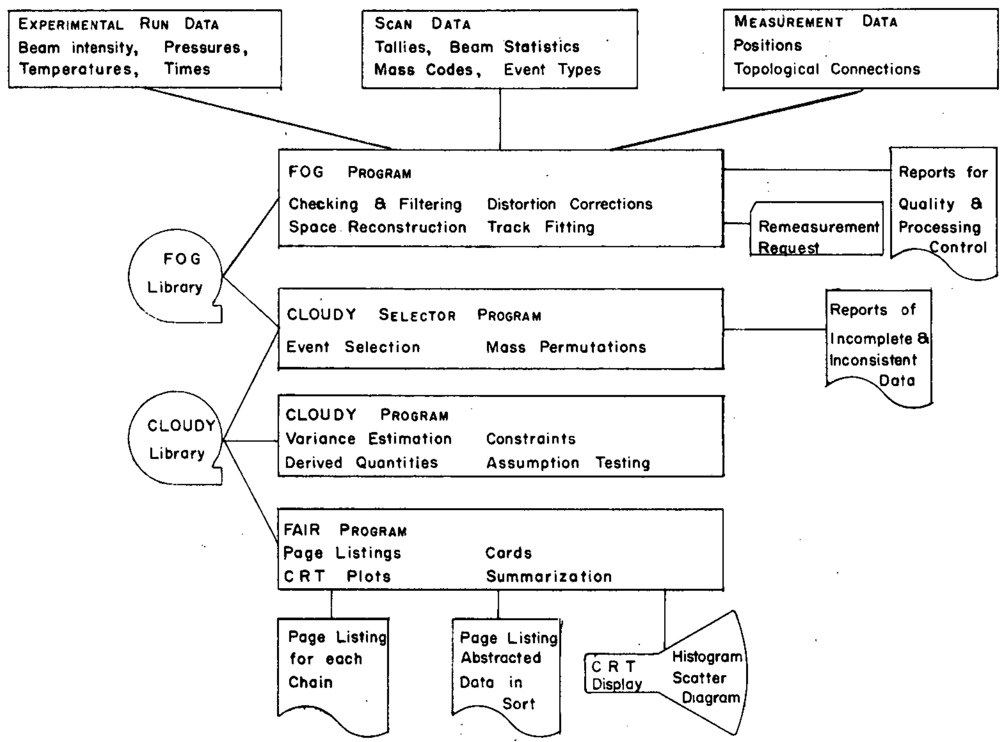
It becomes evident that, as automatic scanning techniques are developed, the correlation of tracks from one view to the next should be done by the program itself and not by scanner assignment of track numbers as is done now. Mass codes must be deduced autonomously, which means that the ionization information that is now evaluated by the scanner and used to assign the mass code must be directly input to the program.

This work was done under the auspices of the U. S. Atomic Energy Commission.



ZN-2606

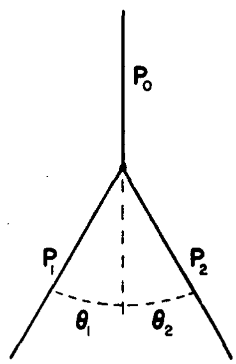
Fig. 1.



MU-21159

Fig. 2.

TWO BODY KINEMATICAL CONSTRAINTS



Constraining Functions

$$F_1 = P_1 \cos\theta_1 + P_2 \cos\theta_2 - P_0$$

$$F_2 = P_1 \sin\theta_1 + P_2 \sin\theta_2 \cos(\phi_2 - \phi_1)$$

$$F_3 = \begin{vmatrix} \lambda_0 & \mu_0 & \nu_0 \\ \lambda_1 & \mu_1 & \nu_1 \\ \lambda_2 & \mu_2 & \nu_2 \end{vmatrix}$$

$$F_4 = E_1 + E_2 - E_0 - M_{TARGET}$$

Constraining Equation

$$M(x_i, a_j) = \sum_{i=1}^{9} \frac{(x_i - x_i^m)^2}{u_i} + 2 \sum_{j=1}^{4} a_j F_j$$

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Fig. 3.