A Reflection on Grid Generation in the 90s: *Trends, Needs, and Influences*

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INTRODUCTION

In a book called *Art and Physics: Parallel Visions in Space, Time & Light*, I read that Newton made reference to "the glory of geometry". This book goes on to point out that the development of perspective was a milestone in the history of art, suddenly opening the 2D canvas to the 3D world. In fact, Renaissance parents urged their children to become professional perspectivists because the skill was in such demand. Grid generation has analogously moved computational simulation from squares and circles into the real world. And, although I didn't suggest the field to my kids, there has been some demand for a few such folks. But our measure of real success is actually in reducing that demand.

That grid generation is a major pacing item (THE pacing item were it not for turbulence) in regard to the use of CFD and other field simulations in industrial design now embarrassingly has the status of a cliche. Twenty years ago, when this sub-field of computational science can be said to have really taken shape, I think we all thought that we would have worked ourselves out of a job by now in the grid area and would have had to go on to find something else to do. I remember at a CFD conference some years ago a perhaps deprecating reference to people making a career out of grid generation, and I never thought of it that way, never thought there was a career in it. But then most of us have done a few other things along the line as well, be it CFD, admin, forming companies, etc. Anyway now a younger generation has come onto the field, and challenges are still there.

And it is a delight to see the enthusiasm and ability of that new generation. When we wrote the grid textbook in 1985, I wondered if there really was a need to include courses in grid generation in graduate programs, if there really were any more good dissertation topics in grid generation or was it just to be coding from then on. But the book sold several thousand copies - even though it is full of typos (the file that went in was actually the penultimate one) - and the dissertations keep coming. It is gratifying that grid generation did not by any means remain a cottage speciality at Mississippi State, but rather innovations have come from all over the world.

But we do continue to incur the impatience of the industrial designers. Much progress has obviously been made, and a number of grid codes are out there at varying costs and of varying utility - in fact most aerospace companies and laboratories seem to have developed their own - but we still have not made the grid generation process easy and automatic. There are several factors that have contributed to that, some of which have always been evident, but I think there may be some others that may have slipped up on us.

So I want to sort of chronicle some of the progress here, raise some thoughts as to why things have gone as they have, and hopefully stimulate some ideas for the future. This is not to be taken as a comprehensive scholarly survey, but rather a consideration of a number of grid papers from the 90s - particularly from the grid conferences, the AIAA Journal, and the Journal of Computational Physics - and directions they may represent. Therefore, I have not attempted to include all papers from the period - there are undoubtedly some significant things that I have missed, with due apologies. But, after five years in admin, the preparation of this paper has certainly been a pleasant return to interesting reading.

Just to document that pacing item cliche for any who don't follow the aerospace literature closely, here are a few recent general observations from industry (with emphasis added).

First, from Ray Cosner at McDonnell Douglas in 1995 (COSNER 1995), who wants a grid on a complete aircraft in six hours:

Surface modeling and grid generation technology have long been recognized as a CRITICAL ISSUE in practical applications of CFD analyses. Surface modeling tools have gained great sophistication in the last ten years. However, the interface to the subsequent CFD analysis codes often is CUMBERSOME and RESTRICTIVE. Without improvements in the process, we can expect the surface modeling and grid generation phase of the process to become a far worse BOTTLENECK in the next few years. The need for specialized skills is a potential CHOKE POINT in the process. This work prior to running the flow solver code consumed about 80% of the total manhours! Clearly, in reducing the manhours and thus the direct cost of CFD analysis we should focus on the tasks of handling the geometry and building the grid.
Pradeep Raj of Lockheed-Martin (RAJ 1995) laments the weeks of grid generation and notes:
Development of a faster flow-solver will have the desired payoffs only if the associated pre- and post-processing tools are also speeded up to permit a significant reduction in the overall turnaround time.
Stuart Connell and collaborators at GE (CONNELL/SOBER/LAMSON 1995) comment:
When computing the flow around complex three-dimensional configurations, the generation of the mesh is the most TIME CONSUMING part of any calculation.
And David Ives and colleagues at Pratt & Whitney (IVES/MILLER/ SIDONS/vanDYKE 1995) call for one-hour grid generation, noting:
Current grid generators may require days to months of elapsed time. The user of a CFD system is not a PhD level CFD specialist but rather a generalist designer. We thus expect our next generation grid generators to be REVOLUTIONARY, not evolutionary.
There are others, but these will surfice. What I really want to do is to take a look at where we are, what factors may have influenced the course, and maybe spur some thinking as to how we can get on to effective and acceptable grid generation systems.

Finally, worth noting is the observation of AFTOSMIS 1995:

Relatively few researchers focus directly on issues surrounding efficient implementation and routine application. Such work is, perhaps, almost unattractive in an environment which rewards novelty and fundamental concepts. However, from an industrial or applications CFD point of view, the automation of routine processes is of paramount importance, and in this polarity lies a serious conundrum.

CURRENT DEMANDS

As Ives says in that 1995 paper cited above: "the designer is the ultimate customer". And this designer is interested in and skilled at design not grid generation. I am reminded of the time August Raspet, an old-time boundary layer control man and founder of the Raspet Flight Research Lab at MSU, was asked how he taught a buzzard to fly in our wind tunnel. Raspet said he gave the buzzard one look at that prop downstream, and that was all it took. That's really the ideal - one look at the geometry and the CFD is on the fly.

We have advanced the supporting grid generation technology very well, to the point that Cosner (above) notes:

Today, it seems fair to state that a satisfactory grid can be developed to model nearly any configuration of interest. The issues at present focus on operational concerns such as cost and quality.
Cosner also notes the early emphasis on non-interactive batch codes, e.g. EAGLE, with which:
The expert could generate tantalizing results which could not be produced, in a practical sense, by the engineer in the design environment.
and goes on to cite the strong positive effect of the move to graphically interactive grid generation systems, e.g. GRIDGEN:
Today, in CFD technology the term "grid generation" is almost synonymous with interactive, graphics-oriented technology. These technologies have enabled the routine generation of usable grids about almost-arbitrary complex shapes of practical interest.
But one requirement that comes through loud and clear is that it must be very simple to change the geometry in the design process. Raj (above) notes that:
The most challenging situation arises when the configuration geometry undergoes changes and multiple analyses have to be performed for each variation. However, that is precisely what the IPPD (Integrated Product and Process Development) design environment requires of CFD!
Connell (above) says:
These GUIs (Graphical User Interface) are of little or no use to a designer who needs to repeatedly mesh and solve on a series of similar geometries.
HUFFORD/HARRAND/PATEL/MITCHELL 1995 of CFD Research Corporation state that:
Factors which separate "good" tools from "bad" tools from the perspective of an applied CFD engineer include: The ease/difficulty and the amount of time necessary to modify the initial grid.
and SCHUSTER 1992 of Lockheed had commented earlier that:
In fact, non-interactive grid generation schemes should thrive as emphasis shifts from development of numerical analysis and design methods to application of these tools to real engineering problems.
This central point may have been overlooked in our press to make it easy to generate grids interactively, and may now being missed again as we try to automate the process. It is not sufficient to just reduce the time to build a single grid for a new configuration when the process has to be redone for design changes. It may be that our push for graphical interaction in grid generation systems, with the idea of making it easier and faster to generate initial grids, may have had the adverse effect of diverting our attention from the critical need for easy and rapid design modifications.

Since much of this support for graphical interaction in the late 80s came from NASA and the Air Force Wright Lab, it is somewhat ironic that MDO (multidisciplinary design optimization) is now causing some rethinking there of these directions. Thus JONES/SAMAREH-ABOLHASSANI 1995 of CSC at NASA Langley state that:

Current grid generation techniques have been strongly shaped by a push to develop interactive tools which aid in the discretization of computational domains. While most of these tools are well suited for the generation of grids about unique configurations, their generality requires a large degree of human interaction. Even for the smallest changes, like those resulting between MDO cycles, a great deal of input of varying degree is needed to redefine the computational structure.
and AFTOSMIS 1995 of Wright Lab describes macros for running angle of attack sweeps as being central to usefulness. Cosner (above) cites the requirement for:
scripting or batch tools for fast parametric variations within new classes of geometry.
Cosner also cites a critical lack of tools for assessment of surface model and grid quality, and notes more complete geometry modeling and higher grid density will become progressively more important in the future as parallel processing enables the solution of larger problems. And both he and Ives (above) say that it must all be put in the hands of a designer, not a skilled grid specialist. The grid generation system must present a default to the engineer and invite modifications, rather than just enabling creation from scratch. These requirements are only further accented by the move towards concurrency in the design process.

We can pass some of the buck justifiably on to the CAD systems since, while it is essential that grid generation systems provide the link between the CFD systems and the CAD systems, Cosner further notes that correcting input geometry defects is a major bottleneck in the process. The grid generation system must be able to remove unwanted detail from the incoming CAD data, and to fix defects such as overlaps and gaps in the CAD model. Yet the quality of the representation of the true surface geometry can be critical to detailed CFD analysis. There must therefore be some CAD-type capability within the grid generation system, but with a direct link to the incoming CAD model. Raj (above) notes that:

Progress in developing streamlined interfaces between grid-generation methods and CAD systems is crucial to reducing the geometry acquisition time.
The incorporation of the NASA-IGES format as a part of this link is a minimum. But MAKSYMIUK/ENOMOTO/vanDALSEM 1995 of NASA Ames note that CAD-to-grid is still a major bottleneck and that:
Despite the advances in standardization by NASA-IGES, the CAD/surface grid interface is still very cumbersome. Without influence on the CAD system vendors - and that has been slow in coming - all this falls by default to the grid generation system: strong motivation for interaction with those vendors. In this regard, it should be appreciated that surface modeling and grid generation extend beyond CFD to to all field problems throughout the design process, and in fact in today's multidisciplinary design optimization, all are linked from the beginning.

Ives (above) goes on to define a list of imperatives for a grid generation system appropriate for design, including:

- handle often imperfect CAD data with gaps, overlaps, tolerances.
- handle scales differing by 5 orders of magnitude.
- automate everything you can, then use graphical interaction for the rest.
- check all user input for range & reasonableness, allow re-entry of data.
- simplicity, lots of feedback on progress, active on-screen help.
- suggest alternatives for corrective action on screen.
- scripting and journal file, batch capability.

Some of these harken back to earlier directions from which attention has since been somewhat diverted.

OPERARATIONAL APPROACHES

The EAGLE grid generation system, first released in the late 80s and now incorporated in EAGLEView, was a completely batch code which created a high level language for grid generation via NAMELIST input. Although this language, preserving each element of the construction of both the surface geometry/grid and the block-structured volume grid, ran on to tens of pages and naturally was time-consuming to write, it did separate the topology from the geometry, and changes to the geometry required only trivial editing. A series of cases could therefore be run with EAGLE in a matter of minutes - thus meeting one important requirement put forth today for grid generators. EAGLE incorporated a hiearchical relationship connecting points, curves, surfaces, and blocks which allowed modifications to be propagated throughout the construction. This connection was achieved through the input language rather than through the data structure, however.

EAGLE (THOMPSON 1987a & 1987b) incorporated a number of features that have later appeared in other codes, some of which are still being resurrected or rediscovered:

- Scipt language describing the entire boundary and grid generation process.
- Hiearchical relationship of surfaces to edge curves to end points.
- Hiearchical relationship of blocks to faces to edges to corners.

- Separation of topology from geometry.
- Rapid editing of geometry.
- Propagation of number of points and distributions throughout configuration.
- Complete continuity across block interfaces.
- Elliptic volume and surface grid generation using control functions interpolated from boundaries or smoothed from initial TFI grid.
- Separate interpolation of spacing and curvature components of control functions.
- Optimum acceleration parameters for SOR iteration in elliptic system.
- Directed differences based on control function sign for first derivatives in elliptic system.
- Incremental iteration of control functions for boundary orthogonality and spacing, operating from control functions based on geometry. Stability control.
- Orthogonality and spacing on both sides of fixed surfaces in field.
- Hyperbolic generation on surfaces and in blocks.
- Complete choice of TFI from faces, edges, corners, or any combination thereof in any dimensionality and direction.
- Lagrange and Hermite TFI blending functions, based on either computational coordinates or interpolated (by TFI) arc length from boundaries.
- Sub-blocks for TFI and control function evaluation.
- Partial-face matching of blocks. Composite surfaces and curves.
- Parametric representation of surfaces by B-Splines.
- TFI and elliptic grid generation, with edge orthogonality, on parametric surfaces.
- Curves on parametric surfaces.
- Surface intersections, with parametric re-gridding on trimed surface.
- Hyperbolic distribution functions on curves.
- Internal geometry generation system.
- Dynamic adaptation and quality with control functions based on combination of geometry and adaptive weight functions.

EAGLE, however, did not have a graphical user interface at all and was consequently not considered attractive by most. (The manual suggested starting with drawing a diagram of the configuration and numbering all elements, a daunting task for complicated bodies in 3D - witness my own attempts at such artistic efforts in THOMPSON/LIJEWSKI/GATLIN 1989.) A GUI was subsequently added to create EAGLEView, which is now freely available, and is still the workhorse code for CFD here at MSU and some other places. (Another interactive interface for surface generation in EAGLE was provided earlier by the IGGy system of PREWITT 1992.)

EAGLEView (REMOTIGUE/HART/STOKES1992, JIANG/REMOTIGUE/STOKES/THOMP SON 1994) preserves the scripting and batch capability of EAGLE, and therefore the ease with which geometrical modifications are made, by writing out the grid generation language (the NAMELIST input) chronicling each element of the generation process now created interactively.

Another factor affecting interest in EAGLE was that, because it was in fact a powerful tool (in the hands of an experienced user - the learning curve was steep) aimed at ease of modification of complicated configurations, other graphically-interactive systems were much easier to use on simplier configurations and were easier to learn. But the command line approach did have power. Particularly ironic now is the observation by VATSA/SANETRIK/PARLETTE 1995 of NASA Langley that:

A batch-oriented approach is needed to make the block-structured grid-generation process more attractive to engineering users. Whenever an interactive module is invoked, an easily understandable and editable script file should be created.

The value of a command-line interface has long been recognized at Boeing (GENTRY 1992), and the AGPS surface geometry system of Boeing (SMIT/SU 1991 & CAPRON/SMIT 1991) provides a structured programming language through which elements of the construction process can be captured and assembled into macros. It is noted by DICKENS 1995 that:
This feature allows repetitive tasks to be easily automated and repeated with little or no user interaction required.
Similarly, ASCOLI/PRUEGER 1995 of Rockwell, in discussing the RAGGS grid generation system and its formation of macros, note that:
Of critical importance to the current effort is the fact that nearly every primary gridding tool available in interactive mode has a nongraphical, "batch" counterpart.
JONES/SAMAREH-ABOLHASSANI 1995 of CSC at NASA Langley, discussing the CSCMDO system, observe that:
Current grid generation techniques have been strongly shaped by a push to develop interactive tools. These methods fall short of satisfying the rapid "hands-off" grid generation needs of CFD in the MDO [Multiplidisciplinary Design Optimization]. Volume grids are generated/modified in a batch environment and controlled via an ASCII user input deck. This allows the code to be incorporated directly into the design loop.
That design and optimization processes use CFD and grid generation in a batch mode was also noted by CHOO/SLATER/LOELLBACH/LEE 1995 from NASA Lewis in 1995.
The need for scripting description of the grid generation process, and the value of batch capability, is thus being rediscovered and carried forward.
The AGPS surface geometry system of Boeing (SMIT/SU 1991), noted above, operates as a geometry programming language to set up surface blocks and grids, creating a command file and macros, and writing the input deck for the surface portion of EAGLE. AGPS includes not only geometrical operations but also mathematical expressions, loops, and commands for controlling the data structure. The BCON system of Boeing (KAO/SU/APPLEBY 1992) is a graphically interactive system for setting the block connectivity and writing the input deck for the volume portion of EAGLE. This system can also serve with other codes.

The GridPro/az3000 system (EISEMAN 1995, EISEMAN/CHENG/HAUSER 1994) of Program Development Corporation, uses a language - Topology Input Language (TIL) - to define both the surface and the block-structured grid. The language includes components (objects) that can be invoked, and therefore admits the formation of element libraries.

The Relational Geometric Synthesis (RGS) of AeroHydro (LETCHER/SHOOK 1995) is a programming or representational language by which points, curves, surfaces, and solids are all linked in a data structure equivalent to a directed graph to capture the design steps and propagate modifications throughout the structure by separating the topology from the geometry.

The GRID* block-structured system of ESA in Europe (HAUSER/PAAP/WONG/SPEL 1991) follows the Unix toolbox concept and consists of a collection of C routines, fairly small in size. Connectivity and orientations are specified by an input file.

The CSCMDO volume grid generator of NASA Langley (JONES/SAMAREH-ABOLHASSANI 1995, KERR/SMITH/POSENAU 1995) takes an initial volume grid from some other generator and adjusts the grid to small changes in the geometry, operating in a batch environment via an input deck. It is significant that the development of this code was prompted by MDO at Langley.

The ENGRID block-structured system of the National Aerospace Lab in the Netherlands, Alenia/Gat, and Fokker (SPEKREIJSE/BOERSTOEL/VITAGLIANO/KUYVENHOVEN 1992, SPEKREIJSE/BOERSTOEL/VITAGLIANO 1991, BOERSTOEL/SPEKREIJSE 1991) uses a connectivity hierarchy from vertices to edges to faces to blocks, allowing compound edges and faces, in which a block can be created by specifying its eight vertices. The generation process is recorded on file.

The MBGRID block-structured grid generation system of Canadair (PIPERNI 1994) uses full-face matching among the blocks, and an inverted tree data structure connecting blocks down to component elements on the wireframe for propagation of point distributions and attributes throughout the configuration to enable modifications. This information is preserved in a script. Libraries of standard wireframes are also created.

The MEGACADS block-structured grid generation system system of DLR in Germany (RONZHEIMER/BRODERSEN/RUDNIK/FINDLING/ROSSOW 1994) generates a command file as the grid is interactively constructed.

The CAMP block-structured system of Lockheed (SCHUSTER 1992) uses script input to construct grids for aircraft configurations in a modular approach.

3DPREP (SORENSON/McCANN 1991) is an interactive system that sets up input for 3DGRAPE of NASA Ames via queries or graphical entries, preserving a history of the dialogue on file. 3DGRAPE is a block-structured system that uses linked lists to describe connectivity between blocks and their components.

The AUTOMAT pre-processor of NASA Ames and Carnegie Mellon (CHYU/RIMLINGER/SHIH 1995) generates the input files for the PEGSUS and OVERFLOW Chimera grid codes via interactive querying.

The IGG block-structured system of Virje Universiteit in Belgium (DENER/HIRSCH 1991) is implemented with object-oriented programming and C++, and operates through interactive dialog boxes to set up the grid components and connectivity. The interactive construction process is saved to file.

In the SAUNA system of the Aircraft Research Association of the UK (SHAW/GEORGALA/MAY/POCOCK 1994), the user works from a planar schematic of the body, creating the block-structured topology by responses to prompts. The surface grids then can be interactively edited. Some automated setup for certain configurations is included. The system also allows the user to remove sections of the structured grid, with triangular grids being then generated on the surfaces so exposed, followed by filling of the void with tetrahedral grids.

CFD-GEOM of CFD Research Corporation (HUFFORD/HARRAN/ PATEL/MITCHELL 1995) has all elements linked so that updates are propagated throughout the database in an interactive system for block-structured grids, tetrahedral grids, and hybrid grids. The system also provides for a library of macros.

The NGP (National Grid Project) system of Mississippi State (A.GAITHER/K.GAITHER/JEAN/REMOTIGUE/WHITMIRE/SONI/THOMPSON/DANNENHOFFER/ WEATHERILL 1995, GAITHER 1994, REMOTIGUE 1994) uses a Boundary Representation (B-Rep) radial edge non-manifold solid modeling topology data structure (following WEILER 1986) which allows explicit connectivity between all geometric and grid entities. Entities are related to components by use-elements which provide adjacency and orientation information in order to abstract the user from the underlying geometric implementations. Orientations of curves on edges, and of surfaces on block faces, are coded using binary indicators for origin, axes, and direction information. The system has explicit adjacencies between volumes and surfaces, via a doubly-linked circular list, which causes surface patches to be automatically glued together and block interfaces to be automatically set up by the code, and which automatically propagates point spacings and distributions throughout the blocks. A recursive depth-first search is used to detect topological blocks in the dataset without requiring user selection. For structured grids, a cycle of four connected edges discovered in the dataset determines a face, while a cycle of six faces then determines a block, all this discovery being done automatically by the code. For unstructured grids, a cycle of connected curves discovered determines a loop, and a cycle of connected faces defined by loops determines a shell. NGP captures the user's actions in a journal file that can be replayed to recreate the generation process in order to make geometric changes within the same topology.

The ICEM-CFD system (WULF/AKDAG 1995, BERTIN/CASTIES/LORDON 1994, AKDAG/WULF 1992, BERTIN/LORDON/MOREUX 1992, delaVIUDA/DIET/RANOUX 1991) from ICEM CFD Engineering captures the users actions in a command file that can be replayed to recreate the generation process and edited in order to make geometric changes within the same topology. A scripting language has also been added. In ICEM, a face is a structured set of subfaces, an edge is made of an arbitrary set of connected curves, and block interfaces are not necessarily whole faces. The user creates the wireframe (the subface edges) interactively, then selects a set of curves to define the subfaces, and a set of subfaces to define the faces. After the user has thus created the wireframe interactively, the code automatically determines the connectivity. The vertices of the wireframe can later be moved without the necessity of re-identification of its components. Point distributions and attributes are propagated automatically throughout the configuration. Actual volume grid generation is done in the batch mode.

In the GRIDGEN system of Pointwise (STEINBRENNER/CHAWNER/FOUTS 1990, STEINBRENNER/CHAWNER/ANDERSON 1992, STEINBRENNER/CHAWNER 1992, STEINBRENNER/CHAWNER 1993, CHAWNER/STEINBRENNER 1995) the user constructs curves which are in turn used to build the topological surface and volume components. The user then selects curves as the boundaries of surface grids, and finally surfaces as the boundaries of volume grids (blocks). With this system, grid generation is a user-in-the-loop task. The data structure maintains the relationship among the curves, surfaces, and volumes so that changes can be propagated up or down the hiearchy automatically. The volume grid generation itself is finally done in the batch mode.

The GEMS block-structured grid generation system of SAMTEK-ITC in Turkey (DENER/KOC/SIRIN 1994 & 1995) is based on object-oriented programming and C++, and uses case-based reasoning and reinforcement learning to capture CFD expertise. The system selects the case that is best suited for a particular geometry from among known ones. The interactive construction steps are captured into macro files that can be edited and replayed.

The UNISG block-structured grid generation system of Fiat and Rockwell (CASELLA/VITALI/BERGAMINI/SZEMA/RAMAKRISHNAN 1994) uses both the conventional elliptic system and also a biharmonic system for boundary orthogonality. The fundamental object here is the edge - with edges, faces, and blocks linked in the data structure so that point numbers are propagated throughout the configuration. The user assembles the configuration interactively.

In the block-structured system of Nissan (FUJITANI/HIMENO 1991) the user selects or draws lines on incoming CAD patches to create the surface block configuration. All block edges are drawn in the field. TFI is then used to generate surface and interface grids. Faces are then selected for each block. Finally, all blocks are assembled into a single block.

SHAW/GEORGALA/PEACE/CHILDS 1991 create a large set of microblocks, typically composed of only eight cells, and then identify the largest computational regions to combine these microblocks into larger blocks.

Finally, the algebraic-topological k-chains of PALMER 1995 may lead to new a programming paradigm relating physical objects, systems, and properties that may prove useful in grid generation.

BLOCK-STRUCTURED GRIDS

Structured grid generation has its roots in the US in the work of Winslow and Crowley at Lawrence Livermore National Lab in the late 60s and in Russia from Godunov and Prokopov about the same time. (There is also that enigmatic Biblical reference to the "four corners of the earth", once thought to proclaim a flat earth but now seen to be a prophesy of grid generation.)

I picked up the idea from reading a 1971 JCP paper by W.H. Chu of the Southwest Research Institute in San Antonio on sloshing in tanks. At that time, Frank Thames was at MSU ready for a dissertation topic. I gave an Open Forum presentation at the first AIAA CFD conference in Palm Springs in 1973, and met Bud Bobbitt and Jerry South of NASA Langley there. They funded the research that became Frank's dissertation - with the cambered rock - and the train was on the track. In the meantime, Yanenko and others in Russia were moving as well, and there was work at Los Alamos.

Another very fundamental component was the work of Bill Gordon at Drexel on transfinite interpolation for the automotive industry, going on independently with GM in the 60s and 70s, and introduced to the emerging grid generation community at the grid conference in Nashville in 1982. (Since the 1st International Conference on Grid Generation was in Lanshut, Germany, in 1986, that one in Nashville has to be the 0th. But then there was the -1st at Langley in 1980.)

Block-structured grids opened the door to real-world CFD in the late 80s, and most real applications are still based on these grids. The idea appears in the proceedings of that 0th grid conference in Nashville in 82 (Rubbert/Lee), but it was the Weatherill/Forsey paper in the AIAA Fluid Dynamics Conference at Snowmass in 84 that really attracted attention to the block-structured approach. Today's structured grid codes, such as EAGLE, GRIDGEN, ICEM, NGP and others noted herein are based on this approach.

Although the grid is logically rectangular within each block, the blocks fit together in an unstructured manner, and JONES 1992 classifies the various types of singularities that may arise at block corners in this configuration. Although block-structured generation systems that maintain complete continuity across block interfaces allow difference representations to be applied on the block interfaces as in rest of the field, MASTIN 1991 gives procedures for representing derivatives on interfaces without line continuity. Complete continuity across block interfaces in the field is accomplished by treating the interface in the manner of a branch cut, with correspondence between points outside one block with points inside the adjacent block.

The now-standard procedure in block-structured systems is to first generate surface grids on block faces - both boundary and in-field block interfaces - from point distributions placed on the face edges by distribution functions. Then volume grids are generated within the blocks. In both this surface and volume grid generation, the first step is normally TFI, to be followed by elliptic generation with control functions interpolated into the field in accordance with boundary point distribution and surface curvature. (This evaluation of control functions is universally known as Thomas-Middlecoff after the 1982 AIAA Journal paper of Thomas of Lockheed. However, the idea actually appears earlier in a rather obscure paper by Shanks & Thompson at a naval hydrodynamics conference at Berkeley in 1977. Ironically, this sequence was reversed with the important advance in this approach made in EAGLE (1987) - separate interpolation of the spacing and curvature components - since this later idea appears in an obscure paper by Thomas in Ireland in 1984.)

The NGP (National Grid Project) system of Mississippi State (A.GAITHER/K.GAITHER/JEAN/REMOTIGUE/WHITMIRE/SONI/THOMPSON/DANNENHOFFER/ WEATHERILL 1995) creates block-structured grids with complete continuity across block interfaces by including block interface and corner points in the elliptic system via logical "sandwiches" formed from the database without duplication of points in storage. EAGLE, by contrast, used an extra layer around each block, duplicating points inside adjacent blocks in storage.

SPEKREIJSE/NIJHUIS/BOERSTOEL 1995 & SPEKREIJSE 1995 give a useful new approach to specifying the control functions of the commonly-used elliptic generation system to reflect boundary point distribution into the field via interpolation of boundary arc length. Fundamentally, arc length is interpolated between opposing boundaries, and the interpolated arc length functions are made to satisfy Laplace equations in physical space. This results in the control functions in the commonly-used elliptic system being defined explicitly in terms of functions containing only the specified boundary arc length distributions and their derivatives thereon. (Earlier work on this approach was given by SPEKREIJSE 1994.) This approach is similar in spirit to the widely-used extensions of the Thomas-Middlecoff control functions that appeared in EAGLE, but this new formulation is more general, and its foundation and derivation are more consistent. The use of cubic Hermite interpolation allows boundary orthogonality to be achieved. Fundamentally, this approach amounts to constructing the control functions for the elliptic generation system by requiring a specified function of XI to have zero Laplacian in physical space rather that specifying the Laplacian of XI in physical space. This has an important extension to the generation of minimal surfaces (soap film), and the grid thereon, bounded by four given edges - a technique that can be of use in generating block interfaces in the field. The interpolated arc length functions are made to satisfy Laplace-Beltrami equations in 3D physical space. The result is simply the addition of the same elliptic equation for z.

The standard approach used to achieve orthogonality and specified off-boundary spacing on boundaries has been the iterative adjustment of control functions in elliptic generation systems, first introduced by Sorenson of NASA Ames in the GRAPE code in the 80s. Various modifications of this basic concept have been introduced in several codes, and the general approach is now common. This general approach is also used by ROSSOW/RONZHEIMER 1991, DOURSAT/PERRONNET 1991, and WHITE 1990.

Boundary orthogonality and off-boundary spacing can, of course, be incorporated as boundary conditions with the biharmonic equation as the generation system, and a recent application of this approach is SPARIS/KARKANIS 1992.

An alternate approach to boundary orthogonality and spacing is to incorporate a hyperbolic generation system near the boundary, transitioning to an elliptic system in the far field as in SPRADLING/NAKAMURA/KUWAHARA 1991 & BACON/HENDERSON/LEE 1994.

Elliptic generation systems operate throughout the entirety of a region, while hyperbolic systems move outward from boundaries. Control functions in each are used to control the grid spacing, orientation, and perhaps other grid quality measures or features of the grid. NIEDERDRENK 1991 uses the control function in a hyperbolic system to sense the outer boundary and adjust the generation accordingly.

JENG/SHU 1995 combine hyperbolic grids marching out from each of four boundaries to generate grids in enclosed 2D regions, preserving or-thogonality near the boundaries. A predictor-corrector scheme is used in the hyperbolic generation systems to reduce oscillations in the grid. Special procedures for dealing with sharp corners are also employed. TAI/YIN/SOONG 1995 use flux splitting, as is common in CFD, to enhance the stability of the hyperbolic generation system through implicit numerical dissipation. CHAN/STEGER 1992 add dissipation explicitly.

EISEMAN/LU/JIANG/THOMPSON 1994 couples Eiseman's control point form (CPF) with EAGLE to speed the generation of large grids by first elliptically generating the sparse control point net with EAGLE and then generating the grid algebraically from these control points by GridPro/sb30XX of Program Development Corporation. The CPF procedure is discussed in CHOO/MILLER/RENO 1991, EISEMAN/WANG 1992, EISEMAN 1991, and LU/EISEMAN 1991, as well as in earlier papers by Eiseman, and is applied in conjunction with conformal mappings in WANG/EISEMAN 1991.

Transfinite interpolation (TFI) has become the standard for algebraic grid generation systems, and is now incorporated in most large codes. As applied in very general form in EAGLE, TFI can accomplish interpolation from any combination of faces, edges, and corners - with boundary orthogonality and with blending functions interpolated from boundary point distributions.

REYMOND/SOTTAS 1994 devise a special form of blending functions based on exponentials to stengthen the control of boundary orthogonality. In this and other works, boundary normals are often averaged over several neighboring points, particularly where the definition of the normal is ambiguous. Although the most common use of TFI is interior to boundaries, interior surfaces may be included for more control. CHAWNER/ANDERSON 1991 use a combination of linear and cubic blending functions, gradually transitioning from cubic to linear away from the boundaries.

SAUNDERS 1994 determines the coefficients of a transfinite interpolation system based on B-splines so as to enhance the orthogonality and smoothness of a 2D interface tracking grid with large deformation of the interface. BERGLIND/ELIASSON 1991 concentrate grid lines in the boundary layer by displacing the surface grids away from the boundary and then filling the void thus created with a grid from univariate TFI.

Structured grid generation may be said to be in generally good shape. It is the automation of the block construction that needs work.

AUTOMATION

As has been noted by VATSA/SANETRIK/PARLETTE 1995 of NASA Langley:
The biggest bottleneck in the grid-generation process occurs at the domain decomposition level. Effort should focus on automating or simplifying the domain decomposition process.
In the literature, there has been some loose use of the term "automation", however. In some block-structured codes, the term has recently been used to mean automated interfacing of blocks after all their edges have been manually created. While this certainly is a desireable element of automation, and one that was not present in earlier codes, it is not yet true automation in the sense of having the block topology itself automatically created.

The critical need for automation of block construction is being approached from several directions.

DANNENHOFFER 1995a creates an abstraction of the geometry to capture the basic topology in order to change the user paradigm from one that is *prescriptive* to one which is descriptive.

DANNENHOFFER 1995b uses simulated annealing to reorganize blocks into an optimum configuration, minimizing an objective function composited of quality measures of the block configuration. The procedure operates by randomly selecting block edges for removal or re-insertion, accepting changes which result in a lower value of the objective function or a value which is not "too much worse" (the definition of which tightens as the process procedes). Since this is a stochastic process, the results are not strictly repeatable; however, differences are not generally large. Topological connections are made interactively on the abstraction and then are linked to the geometry.

This technology has been incorporated into the NGP (National Grid Project) system of Mississippi State (A.GAITHER/K.GAITHER/JEAN/REMOTIGUE/WHITMIRE/SONI/THOMPSON/DANNENHOFFER/ WEATHERILL 1995). The NGP system has explicit adjacencies between volumes and surfaces, via a doubly-linked circular list, which causes block interfaces to be automatically set up by the code, and which automatically propagates point spacings and distributions throughout the blocks. A recursive depth-first search is used to detect topological blocks in the dataset without requiring user selection.

The ICEM-CFD system (WULF/AKDAG 1995) from ICEM CFD Engineering creates some initial blocking automatically based on bounding boxes and certain recognizable components. The user then makes connections to the geometry and splits the blocks to arrive at a suitable block configuration.

Two attempts at truly automatic block construction in 2D are given by SCHONFELD/WEINERFELT/JENSSEN 1995: one based on advancing front and another based on recursive subdivision. In each approach, the boundary is first made one continuous loop curve by manually connecting separated parts. The advancing front moves from this boundary creating a coarse unstructured hexahedral grid. Since this tends to create a relatively large number of cells, neighboring cells are merged manually to create the final blocks. The recursive subdivision approach creates a cut between a selected boundary point with a high degree of convexity and another suitable boundary point, thus splitting the initial single boundary loop into two loops. That suitable point for the terminus of the cut is chosen so that the resulting two loops minimize a function composited of several block quality measures. This procedure is then repeated until no boundary points with large convexity remain and all blocks have 3-5 corners. Triangular and pentagonal blocks are then subdivided into rectangles. In each case, a linear programming problem is solved to propagate numbers of points on block sides throughout the configuration. The recursive subdivision procedure tends to produce larger and much fewer blocks. The success of the subdivision procedure is highly dependent on the definition of the block quality function. Earlier work for 2D was in SCHONFELD/WEINERFELT 1991.

STEWART 1992a & 1992b, in 2D, uses a search tree with a small set of rules to drive directional probing from the boundary to search for an appropriate block decomposition, in analogy with balloons inflating against each other: a coarse approximation to the perimeter of a region so that it conforms to neighboring boundaries without excessive stretching.

A 3D use of advancing front to automate block construction by generating coarse hexahedral cells is given by KIM/EBERHARDT 1995. The front is advanced on directions that take into account both local and neighboring normals to the body surfaces. The approach is a predictor/corrector with the entire front being advanced and then Laplacian smoothed between the old front and an image of the old front with respect to the new front. The distance and general direction of advancement are user controlled. The method tends to create a large number of relatively small blocks, since all are full-face matched.

SHAW/WEATHERILL 1992 use a schematic representation of the geometry, whereby all component elements are made planar or cuboid, and a globally cartesian (H) block structure is created with C and O type topologies embedded around certain components by introducing diagonal hypercube-like cuts.

DENER/KOC/SIRIN 1994 & 1995 use case-based reasoning and reinforcement learning to capture CFD expertise to set the block configuration. The system selects the case that is best suited for a particular geometry from among known ones.

As in Rossetti's Choice, there is yet more sea.

OVERSET GRIDS

The Chimera (overset) approach, pioneered by Benek, Buning and the late Joe Steger in the 80s, has great versatility and is especially attractive with bodies in relative motion. (Joe Steger was one of the true giants in both grid generation and CFD, and his early death - ironically, while many of us were at the 92 grid conference at Langley - was a huge loss to the field.) There was a symposium specifically on the subject of overset grids at Eglin AFB in 1994. The method has, however, never attracted as many users as might have been expected. BELK 1995 notes that considerable user experience and interaction is required to determine how to combine the component grids.

Present centers of application are NASA Ames with Overset Methods (MEAKIN 1995b & 1995c), the Air Force AEDC (the PEGSUS system), the Air Force Wright Lab at Eglin (BELK 1995), NASA Johnson, and IBM. Concerns have been continually raised about the accuracy of the interpolation necessary to transfer data between component grids, and particularly the lack of conservation that is attendant. MEAKIN 1995b, however, argues that grid resolution is the primary issue, and that:

An effective adaptive grid technique appropriate for systems of overset grids should be viewed as the primary remedy for issues relating to conservation at grid interfaces.
Meakin's recent direction (MEAKIN 1995a) has been to overlay the Chimera near-body grids on a set of overlapping adaptive cartesian off-body grids. (This general approach is also taken in the FAME system of ONSLOW/BLAYLOCK/ALBONE/HODGES 1994 & ALBONE 1992.) The cartesian off-body grids are generated by coalescing elements of a fixed "master brick" which are tagged according to spacing on proximate curvilinear near-body grids.

The BEGGAR system of BELK 1995 & MAPLE/BELK 1994 operates with an input file that provides the necessary information to allow the code to establish block connections, hole cutting, and overlapped connections in a multi-block Chimera (overset) grid using several multiply linked, independent lists. The system uses an octree data structure with many small binary space partition trees to locate intersecting regions and to provide in/out determination.

JOHNSON/BELK 1995 treat the overlapping grids as independent levels of a multigrid full approximation scheme, as an alternative to boundary point interpolation. WANG 1995 creates a patch boundary in the overset region in order to achieve conservative flux representation. LIN/PERCIVAL/GOTIMER 1994 apply the Chimera approach (using PEGSUS) to ships with appendages. CHAWLA/BANKS 1993 use overset grids to track developing flow features in time-dependent solutions.

Another overset approach is to employ a hierarchy of embedded cartesian grids as in PEMBER/BELL/COLELLA/CRUTCHFIELD/WELCOME 1993 & 1995.

I still believe that the overset approach has not been given attention comensurate with its potential, especially now that distributed computing is coming to the fore.

UNSTRUCTURED GRIDS

Unstructured grid generation has its roots in the finite element world of structures modeling. The real introduction to the CFD community came in the 80s primarily from Baker, Weatherill, and Lohner. Unstructured grids have inherent simplicity of construction in that, by definition, no structure is required. Also it is not inherently necessary to communicate the actual topology of the configuration to the grid generator.

Although largely synonymous with tetrahedral grids, unstructured grids may alternatively be composed of hexahedral cells (without directional structure). The term might strictly encompass any combination of cell shapes, but in the grid generation literature combinations of regions with structure (e.g. structured or prismatic grids near body surfaces) with regions without structure are generally called hybrid grids. For that matter, block-structured grids are unstructured in the large.

There are fundamentally three approaches to the generation of tetrahedral grids that have attracted the most interest in CFD (cf. BAKER 1995, AFTOSMIS 1995): Octree, Delaunay, and Advancing Front. Other approaches are noted as well in the good historical summary given by FIELD 1995, where it is observed that there has been a "notable shift from mathematical formulas toward procedural algorithms that emphasize geometric computations" over the last ten years.

Octree, stemming from the pioneering work of Shephard at Rensselaer in the 80s, is the most simple in that cubes containing body surface segments are recursively subdivided into eight cubes until a desired resolution is reached, whereupon irregular polygonal cells are created from the cubes intersecting body surfaces, and then tetrahedral cells are created from these cells and the remaining cubes (WEBSTER/SHEPHARD/RUSAK/FLAHERTY 1994 is a recent application).

This procedure is also followed by SMITH/JOHNSTON 1994, using binary tree data structures for both the cartesian grid and for boxes enclosing the surface patches to enable the necessary repeated searches for intersections of the cartesian cells with the surface patches. This approach requires the least of the surface representation, since only the irregular cells intersecting the surface are created rather than an actual grid on the surface. This is, however, also a drawback in that a desired surface grid cannot be matched. The underlying subdivided cubic structure also shows through, with its rapid variation in cell size, until smoothing is applied. The data structure is, however, attractive for its simplicity.

The Delaunay approach, tracing in CFD largely to Baker and Weatherill working together in the 80s (later MITTY/BAKER/JAMESON 1991, CHILDS/WEATHERILL 1991, WEATHERILL/HASSAN/MARCUM 1993) incorporates inherent grid quality features while allowing control of grid resolution. Fundamentally, each point has a separate region which is closer to that point than to any other point. Starting from a coarse triangulation created from only the boundary points, points are inserted according to resolution specifications, commonly obtained from a background grid, and the triangulation is locally reconstructed according to the Delaunay criterion that the circumsphere through the four vertices of a tetrahedral cell does not contain any other grid point. The Delaunay approach features efficiency and a sound mathematical basis. But the Delaunay procedure connects points - the points have to be defined by some other procedure. Although this can be done by octree subdivision of the field, the more common approach is to insert new points within the tetrahedra as they are created, starting with very coarse elements connecting boundary points across the field and continuing until element size criteria, normally interpolated from the vertices of the original coarse grid, are satisfied. Adaptive refinement can follow the same point insertion and local re-triangulation approach.

The main difficulty with the Delaunay approach is that insertion of certain additional points on boundaries is necessary to preserve surface integrity, since the connection of points does not inherently recognize boundary segments as such. Either the Delaunay criterion must be relaxed near the boundaries, or boundary points are added as necessary to avert breakthrough of the boundary, or - as is now more common - the grid is post-processed with a defined set of element transformations to reconfigure elements breaking through the boundary (WEATHERILL/HASSAN/MARCUM 1993).

The Delaunay approach creates tetrahedra from a set of points, but the operation is sequential in any case. REBAY 1993 takes advantage of this fact to insert points one at a time to meet specified spacing criteria. One possibility is to insert the point at the circumcenter of the cell most deviant from the spacing criteria. Another is to insert on the line joining the circumcenters of two adjacent cells, one of which already meets the spacing criteria. The second approach was found to give better grid quality.

BAKER 1994 and MARCHANT/WEATHERILL 1994 discuss the use of the Delaunay approach, including the generation of high aspect ratio triangles in boundary layers. Surface normals are smoothed over several neighbors in order to set spacing directions off the surface. In the latter work, the cells near the boundary are created one layer at a time by a form of advancing front.

HAMANN/CHEN/HONG 1994 insert points into an initial Delaunay grid in accordance with distance from the boundary and the boundary curvature there. ANDERSON 1994 adds points in accordance with cell aspect ratio and proximity to boundary surfaces. The Delaunay criterion may not, however, be the most appropriate for high-aspect ratio elements or sliver elements.

Advancing Front, introduced in CFD primarily by Lohner and Peraire from Swansea in the 80s, builds the tetrahedral cells progressively outward from the triangulated body surfaces, with element size guided by some distribution function, often interpolated from some background grid. The surface triangulation is thus inherently preserved. Special procedures are necessary to keep fronts which are advancing towards each other from overlapping. And smoothing and repair may also be required where fronts meet. Significant data searches are required as new cells are built on the advancing front since vertices suitable for connections must be located on the front, and checks for intersections with existing elements must be made. This searching can be localized by testing the cell bounding sphere against the bounding box in an octree decomposition of the region (STEINBRENNER/NOACK 1995). FORMAGGIA 1991 uses a multidimensional alternating direction binary search tree and a succession of constrained minimizations.

MULLER 1994 uses a frontal Delaunay approach to build high aspect ratio triangles outward from the boundary, switching to isotropic outside this inner region. Vertices are inserted into an initial Delaunay triangulation, first to define the extent of the inner region which is filled with high-aspect ratio stretched wedges by outward marching layers. The remainder of the region is then filled with triangles, using the Delaunay triangulation as an efficient search structure.

MAVRIPLIS 1993 uses an advancing front approach to determine the order of Delaunay point insertion in 2D, adding new points ahead of the front and triangulating them according to the Delaunay criterion, using a quadtree data structure to locate neighboring points and triagles on the front. A combination of Delaunay and advancing front was also given by MERRIAM 1991.

LOHNER 1993 grows prisms outward from boundaries according to smoothed surface normals and then divides the prisms into tetrahedra. Outside these inner layers, advancing front takes over to complete the grid.

HASSAN/PROBERT/MORGAN/PERAIRE 1994 use advancing front to generate tetrahedral grids, following a layer-by-layer approach in boundary layers. After a single layer of tetrahedral cells has been created on the boundary, the newly-generated points are moved along along the cell edges towards the boundary to a specified distance. This procedure is repeated until a specified number of layers has been created, after which the advancing front procedes to fill up the remainder of the field in the conventional manner.

The layered approach was also used by PIRZADEH 1994, basically creating a prism along surface normals from the three vertices of a surface triangle and then dividing the prism into three tetrahedra. The layers stop advancing when the element spacing determined by the stretching function locally matches that from a background grid. A spring analogy is used to create forces that stop the advancement of approaching layers before overlap occurs. Conventional advancing front takes over to generate the grid in the bulk of the field after all the layers stop.

MARCUM 1995 also uses a layered approach, first generating high-aspect ratio elements outward along boundary normals and then using advancing front in the remainder of the field. Local reconnection for optimization is used throughout the process, and smoothing is applied in the field at large. Element size is controlled by a distribution function interpolated from boundary points or specified for geometric growth normal to the boundary. A valid grid is maintained throughout the process, allowing efficient searching through a simple data structure. The procedure is quite fast, so that a PC is sufficient in 2D and a workstation is adequate in 3D. The overall advancing front and local reconnection procedure for the bulk of the field appears in MARCUM/WEATHERILL 1994a & 1995.

PRIZADEH 1992 & 1993 obtains the distribution by solving a diffusion equation on a background uniform cartesian grid on which are placed prescribed source elements. WEATHERILL/HASSAN/MARCHANT/MARCUM 1993 use distributed sources rather than a background grid.

BARTH/WILTBERGER/GANDHI 1992 give an incremental triangulation algorithm based on point insertion and local edge swapping to optimize user-specified quality measures.

Unstructured hexahedral grid generators in 3D are less well-developed, but are progressing. One approach is to base the procedure on triangle/tetrahedral generators, and several works in that direction were noted in THOMPSON/WEATHERILL 1993. Another approach that has been pursued for some time is that of paving (BLACKER/STEPHENSON 1991), following work at Sandia. The 2D region is paved by rows of quadralateral cells outward from boundaries, with much cutting and stitching.

SCHNEIDERS/OBERSCHELP/WEILER/KUPP/BUNTEN/FRANZKE 1994 & SCHNEIDERS/BUNTEN 1995 generate a hexahedral grid by first filling the region with a regular cartesian grid of cubic cells, stopping a certain minimum distance from the boundaries. Exposed corners of cubes are then connected to the boundary according to 12 classes of situations, with some special treatments also required in some cases. IVES 1995 uses the approach of embedding surfaces in a base grid, cutting out intersections, and then snapping the surface into the base grid. KREINER/KROPLIN 1994 and TANIGUCHI/FILLION/SAUTY/ZIELKE 1994 create quadrilateral surface grids by combining triangles.

MAGNAN/MASSE 1994 generate a quadrilateral grid on one side of a block and then extrude that grid through to the opposite side of the block, mapping the quadrilateral grid onto successive cross-sections in the block by TFI. The 3D grid in the block is thus fully structured in the extrusion direction. The procedure can then be repeated into compatible adjacent blocks.

Another fundamental approach to hexahedral grid generation is to simply use the techniques of block-structured grid generation, with the blocks as large unstructured hexahedral bricks, created by any means available, within which a structured - and therefore inherently hexahedral - grid is generated by TFI or elliptic systems. This approach - with TFI - actually predates later approaches, as noted by FIELD 1995, but its potential may currently be underevaluated.

Finally, LOHNER 1995 considers several search algorithms for interpolation between unstructured grids composed of the same type of elements.

HYBRID GRIDS

Both unstructured tetrahedral grids and recursively subdivided cartesian grids are unacceptably inefficient for high Reynolds number solutions because of the lack of high aspect ratio cells near body surfaces. Although both approaches can do Navier-Stokes solutions, the number of cells required renders the point moot. BAKER 1995 notes that the truncation error of a finite volume discretization depends on the shape of the control volume, and AFTOSMIS 1995 notes that difficulties exist also in resolving wakes and other free shear layers. This has naturally led to interest in hybrid grids - tetrahedral or cartesian away from the body surfaces, with some structure admitting effective high aspect ratio cells near those surfaces.

One such approach is to use prismatic grids near the surfaces. Here the surface is triangulated, and connected prisms are grown out from those surface triangles via advancing fronts moving generally normally out from the surfaces. The marching directions for the advancing front must take into account not only the local surface normal but also those of adjacent surface points in order to keep the front regular off both convex and concave regions of the body surfaces. Careful attention must also be paid to the marching step size. And smoothing may be necessary on both the marching direction and step size. Some provision must be made to keep two fronts approaching each other from two different bodies from intersecting. The layers in the prisms are distributed to resolve the boundary layer. These prismatic cells near the body can thus have very high aspect ratio, yet have no small angles as would be the case for tetrahedral cells.

KALLINDERIS/WARD 1993 & WARD/KALLINDERIS 1993 generate an inner prismatic grid by placing points at the intersection of adjusted surface normals with a smoothed parallelepiped voxel representation of the present front. This has the effect of a gradual inflation of the body volume, reducing the curvature of the outward marching surface at each level. Grid points are distributed on splines of the resulting marching lines. The outer tetrahedral grid is generated by successive octree refinement, dividing octants into tetrahedra. Boundary octants on the outer surface of the prisms are truncated to form boundary polyhedra which are then divided into tetrahedra.

KALLINDERIS/KHAWAJA/McMORRIS 1995a & 1995b and KHAWAJA/McMORRIS/KALLINDERIS 1995 embed the prismatic grid in a tetrahedral grid away from the bodies. The tetrahedral grid in generated by advancing front using an octree-type cartesian grid as the background grid to control resolution. The front procedes outward from the outer surface of the prismatic grid. An automatic receding method of pulling back the advancing prismatic grid fronts when two approach each other is employed, together with redistribution of points on the splined edges of the prisms. Grid refinement is used only in the tetrahedral grid, carrying refinement of surface triangles throughout the prismatic layer in order to avoid changing the structure of that layer. Points are redistributed along the prism edges dynamically to resolve the boundary layer.

MARCUM 1995 combines tetrahedral elements into prisms near the boundary. HWANG/WU 1993 & 1992 combine triangles into quads when the common side is the longest side of those two triangles. CONNELL/BRAATEN 1995 generate prismatic cell layers outward according to adjusted surface normals, then adjust the front by collapsing certain prismatic cells into pyramidal or tetrahedral cells in problem regions, and finally generate a tetrahedral grid in the bulk of the region using advancing front.

STEGER 1991 and MELTON/PANDYA/STEGER 1993 use a hyperbolic grid generator to extend the prismatic grid outward from the boundary. MAVRIPLIS 1991 uses a hyperbolically-generated grid about each body and attached wake line to guide the formation of high aspect ratio triangles near the body.

KARMAN 1995 embeds the prismatic grid in an octree-type cartesian grid away from the bodies, with the resolution of the cartesian grid matched to the surface triangulation. The outer surface of the prismatic grid replaces the body surface for connection to the cartesian grid.

STEINBRENNER/NOACK 1995 build a hybrid grid on the Chimera approach, generating block-structured grids around each body as in Chimera, cutting holes where these grids would overlap, and then filling the holes with tetrahedral cells via advancing front. The holes are formed by first removing intersecting logically rectangular sub-blocks formed by successive subdivision of the structured grids, and then concatenating the remaining sub-blocks when possible. The front is advanced from the resulting exterior sub-block boundaries, first by adding hexahedral cells fitted to those in the structured grids, and finally, when this process would produce overlap, building tetrahedral cells on the front from then on. User interaction is required to produce acceptable constructions.

KAO/LIOU 1995 follow a similar approach in 2D but maintaining the outer boundary of the body grids intact while removing intersecting cells from the outer (cartesian in the results given) grid. The voids between grids are then filled with triangles using the Delaunay approach. And a similar approach is also followed by

SHAW/GEORGALA/CHILDS 1994, SHAW/GEORGALA/PEACE/CHILDS 1991, and CHILDS/WEATHERILL 1991 with a layer of pyramidal elements effecting the transition from the hexahedral grids to the tetrahedral grids.

ASHBY/FITZSIMONS/FOWLER/GREENOUGH 1991 use triangles to transition between regions of cartesian grids. KALLINDERIS/NAKAJIMA 1994 use triangles to transition regions of differing levels of adaptation in structured grids.

CARTESIAN GRIDS

There has always been a natural yearning for cartesian grids through the years. Cartesian grids continue to be attractive because of their inherent simplicity and potential for automation through recursive subdivision with a octree data structure as in COIRIER/POWELL 1995, MELTON/BERGER/AFTOSMIS/WONG 1995, KARMAN 1995, KINARD/SCHABOWSKI 1995, MELTON/ENOMOTO/BERGER 1993, AFTOSMIS/MELTON/BERGER 1995, deZEEUW/POWELL 1993. Also it is not necessary to communicate the actual topology of the configuration to the grid generator. The intersection of the cartesian cells with the boundary triangulation is made more efficient by the use of an Alternating Digital Tree data structure which makes it possible to identify the list of surface triangles which span a given cartesian cell.

The cubic cells are repeatedly split into eight cubes locally until necessary resolution is achieved. Polygonal splitting is used on the cells intersecting body boundaries to create irregular polygonal cells there fitted to the boundary. Cell sizes thus may vary by many orders of magnitude over the field, yet all are cubic except for the irregular polygons surrounding the body surfaces. The grid generation is, however, completely automatic once the boundary surfaces are in place, and the approach is much more tolerant of the incoming CAD data since it is only necessary to construct the irregular polygons intersecting the surfaces, not actual grids on the surfaces. The approach also extends inherently to adaptive grid refinement without change in the data structure. Clearly, any desired level of accuracy can be achieved with sufficient subdivision of cells. The price of this simplicity and automation is, however, a very large number of cells. And in adaptive refinement, cells cutting the boundary must be constantly tested against the surface database.

AFTOSMIS/MELTON/BERGER 1995 enhance the accuracy of the boundary treatment by triangulating the portion of the surface intersected by each cartesian cell, operating from the original surface parametrization, e.g. triangulated NURBS. This results in several triangular cells for each cartesian biundary cell, thus greatly increasing the total number of surface triangles.

While working well for Euler solutions, cartesian grids suffer from the same problems found with unstructured tetrahedral grids in high Reynolds number Navier-Stokes solutions: an unnecessarily large number of cells because of the inability to use high aspect ratio cells near the body surface. Resolving boundary layers with cartesian grids is thus inherently inefficient (AFTOSMIS 1995).

SURFACE GRIDS

As has been noted above, generation of a satisfactory surface grid remains a major bottleneck in the grid generation process, largely stemming from the fact that CAD systems adequate for numerical machining are not necessarily adequate for numerical simulation. AFTOSMIS 1995 rates surface triangulation as the most time-consuming and user-intensive operation. GATZKE/LaBOZZETTA/COOLEY/FINFROCK 1992 at McDonnell Douglas noted that:

Experience has shown that one-third to one-half of the time between obtaining point surfaces from CAD and completing the grid is spent manipulating the geometry into the form desired for the application at hand. Grid generation systems must be able to take CAD data as it comes - with gaps, overlaps, various definitions, etc. (Cosner, Ives, Maksymiuk - all cited above - and KERR/SMITH/POSENAU 1995, HUFFORD/HARRAND/PATEL/MITCHELL 1995). The general approach is to cover the incoming CAD patches in some manner with a regular set of patches on which a grid is generated and then transferred to the underlying CAD patches. This approach was pioneered by the ICEM-CFD system (WULF/AKDAG 1995, BERTIN/CASTIES/LORDON 1994, AKDAG/WULF 1992, BERTIN/LORDON/MOREUX 1992, delaVIUDA/DIET/RANOUX 1991) from ICEM CFD Engineering which reads CAD data via IGES or other formats, converts to NURBS, generates grids on TFI surfaces bounded by curves on the input patches, and then projects these grids onto the input CAD patches. Such projection onto the input patches is also used in the Nissan system (FUJITANI/HIMENO 1991).

The GridTool utility of NASA Langley and CSC (SAMAREH-ABOLHASSANI 1995, KERR/SMITH/POSENAU 1995) effects this transfer by generation of structured or unstructured grids on bi-linear patches followed by projection onto the original CAD patches. SAMAREH-ABOLHASSANI 1994 approximates input NURBS surface patches with a set of smaller bilinear patches, generates a triangular grid on these smaller patches via advancing front, and then projects this grid onto the NURBS patches, smoothing and re-projecting as necessary.

The NGP (National Grid Project) system of Mississippi State (A.GAITHER/K.GAITHER/JEAN/REMOTIGUE/WHITMIRE/SONI/THOMPSON/DANNENHOFFER/ WEATHERILL 1995) reads CAD data via IGES and converts all surface patches to NURBS. A carpet, composed of interfacing NURBS patches, is then laid over the CAD patches to correct for gaps and overlaps. Surface grids are generated on the NURBS carpet, and can be projected onto the original CAD patches. The carpet is, however, coincident with the CAD patches, except for deficiencies in the latter, so this projection is largely moot. This carpet (JEAN/HAMANN 1994) operates by specifying four boundary curves (patch edges or constructed curves) on the input patches, generating a surface from these four curves by TFI, and then projecting this surface onto the underlying surface patches. The resulting projection is then made a NURBS to form the carpet lying on the surface patch system. This carpet patch may cover all or parts of several input surface patches from the CAD system, including gaps and overlaps. An octree data structure is used to store the triangulation of the input patches in order to enable efficient search in the projection. Hardy's reciprocal multiquadratic bivariate scattered data approximation is used in the projection to fill gaps between the input patches. The set of NURBS carpet patches in then unioned to cover the entire body. Since the NGP system interfaces with CAD systems via IGES files, the carpet generation is facilitated by first converting all input surface patches from IGES to NURBS (YU/SONI 1994 & YU/SONI/SHIH 1995). This allows the projection to operate in a consistent manner regardless of the source of the input patches.

The RAGGS system of Rockwell (WOAN/CLEVER/TAM 1995) covers incoming CAD patches with quilts of NURBS and/or rational Bezier patches, generates surface grids from edges in space by TFI, and then projects these grids onto the quilts. GRIDGEN of Pointwise (CHAWNER/STEINBRENNER 1995) reads CAD data via IGES and uses Nth-degree rational Bezier curve and surface geometry internally. In the UNISG block-structured grid generation system of Fiat and Rockwell (CASELLA/VITALI/BERGAMINI/SZEMA/RAMAKRISHNAN 1994) input IGES files are converted to NURBS, and the surface grids are generated on these NURBS.

The use of fundamental concepts from differential geometry to formulate the Laplace-Beltrami generation system for surface grids was pioneered by Warsi in the 80s (also WARSI 1990, WARSI/KOOMULLIL 1991). ARINA/CASELLA 1991 use a surface elliptic system derived from harmonic mapping.

The EAGLE system (THOMPSON 1987a & 1987b) incorporates this approach on a surface construction based on B-splines, with which surface blocks could be built, split, and concatenated. Surface intersections were calculated by 3-parameter Newton iteration as one surface was inserted into another. Curves on the surface could be constructed in parameter space, and surface grids were generated in parameter space by both TFI and elliptic systems. (EAGLEView now includes hyperbolic as well.) This general approach has been followed in several later works such as LAUZE/CAMARERO/YANG 1991.

The SDL surface description language of AF Wright Lab at Eglin (MAPLE 1992), with roots in EAGLE, is a portable high-level interpreted language optimized for surface manipulation.

In the MEGACADS block-structured grid generation system system of DLR, Germany, (RONZHEIMER/BRODERSEN/RUDNIK/FINDLING/ROSSOW 1994) uses the Laplace-Beltrami operator in a fourth-order elliptic system to formulate a surface grid generation system in parameter space that has boundary orthogonality and is independent of the parametrization.

SPEKREIJSE/NIJHUIS/BOERSTOEL 1995 give a new approach to elliptic grid generation on surfaces. Fundamentally, arc length is interpolated between opposing edges, and the interpolated arc length functions are made to satisfy Laplace-Beltrami equations in the parametric space of the surface. Control is achieved implicitly through the specification of the arc length distribution on the edges. The use of cubic Hermite interpolation allows orthogonality to be achieved at the edges.

Surface grids have also been generated in terms of the physical coordinates, instead of the parametric coordinates, using repeated projection back onto the defining surface patches in the course of the iteration to preserve the specified surface shape, as in STEGER 1991 for hyperbolic surface grids. Use of the physical coordinates without this projection, as has appeared in the literature, does not preserve the specified surface.

The system of KREINER/KROPLIN 1994 surveys input CAD patches for apparent connectivity in order to automate the construction of a connected network of surface patches on which unstructured grids are generated. A parameter plane is inserted between the surface patch and the surface grid in order to remove the effects of the parametrization on the grid.

SUZUKI 1991a & 1991b represents the surface by polygonal patches and then solves an elliptic grid generation system in physical space on the surface by a Galerkin finite element approach to generate a structured grid on the surface. This same general approach is followed also by NAKAMURA/FRADL/SPRADLING/KUWAHARA 1991. AFTOSMIS 1993 also uses a surface tessalation.

DESBOIS/JACQUOTTE 1991 parameterize the two families of curves through an input surface array separately by normalized arc length. The arc lengths within each cell of this array are then represented by Hermite patches based on the values and derivatives at the four corner points evaluated by finite differences. The map of physical coordinates on the surface from the arc length parameterization for each cell is then created as a Hermite patch with the derivatives evaluated analytically at the four corners from the arc length patches. This amounts to surface representation from two families of spline curves instead of construction a two-dimensional spline, as in the more commin approach.

The S3D surface system of LUH/PIERCE/YIP 1992 & LUH/YIP/PIERCE 1991 acquires surface sections as sets of cross-sections, and then provides facilities for patch construction on this surface definition.

Interaction between the builders of grid generation systems and CAD systems is sorely needed.

ADAPTIVE GRIDS

Grid adaptation is carried out by some combination of redistribution (moving the grid points), refinement (adding/deleting grid points), or modification of the solution representation on the grid. Redistribution has been the favored approach with structured grids, refinement with unstructured grids, and little use has been made of the third approach in real CFD applications. Numerous papers have addressed refinement of unstructured grids, as this is, in fact, a natural strength of that approach. Good examples are found in the Barcelona and Swansea grid conference proceedings, e.g., WEATHERILL/SONI 1991. Other examples are KALLINDERIS/VIJAYAN 1993 where tetrahedra are divided into eight cells with special care to eliminate hanging nodes, WEBSTER/SHEPHARD/RUSAK/FLAHERTY 1994 adding nodes at the mid-points of cell edges, and BISWAS/STRAWN 1993 with three types of subdivision. Refinement often includes remeshing after point insertion to maintain Delaunay criteria. Smoothing is also common.

SCHONFELD 1994, EVANS/MARCHANT/SZMELTER/WEATHERILL 1991, and SZMELTER/MARCHANT/EVANS/WEATHERILL 1991 are recent examples of refinement with structured grids, the latter actually creating a hybrid grid by using triangular elements to treat the hanging nodes that occur when quadralaterals are subdivided adjacent to undivided cells. Another recent example is AFTOSMIS 1994, using both pyramidal and prismatic cells around hanging nodes. DAVIS/DANNENHOFFER 1994 subdivide all cells in logically rectangular sections in the same manner to preserve a block structure. KALLINDERIS/NAKAJIMA 1994 use triangles to transition regions of differing levels of adaptation in structured grids.

Combinations are also used, of course, with redistribution perhaps following refinement in unstructured grids as a smoothing operation as in RICHTER 1994.

Dynamic adaption of the grid to the developing solution has long been based on physical analogies - springs and such, as in SAOUAB/VANDROMME 1991, HARVEY/ACHARYA/LAWRENCE/CHEUNG 1991, HARVEY/ACHARYA/LAWRENCE 1992, HARVEY/ACHARYA/LAWRENCE 1993 and earlier work of Nakahashi & Deiwert, Gnoffo and others. The SAGE code of DAVIES/VENKATAPATHY 1992 incorporates the Nakahashi & Deiwert work. KNUPP 1995 uses concepts from continuum mechanics, as has Jacquotte. And adaptive sources may be introduced, particularly in unstructured grids as in MARCUM/WEATHERILL 1994b & 1995, using an octree to locate nearby sources in the adaptation process. Sources are also used by WEATHERILL/HASSAN/MARCHANT/MARCUM 1993.

MARCUM/WEATHERILL/MARCHANT/BEAVEN 1995 separate flow features into boundary layer, detached viscous, and inviscid. Adaptation in the boundary layer is along boundary normals; streamlines from boundary discontinuities are introduced as pseudo-surfaces to guide adaptation in the same way for detached viscous regions; and adaptation sources based on gradient strengths are used in the bulk of the flow.

PARTHASARATHY/KALLINDERIS/NAKAJIMA 1995 & PARTHASARATHY/KALLINDERIS 1995 use grid refinement only in the tetrahedral grid of a hybrid grid with prisms near the boundary, carrying refinement of surface triangles throughout the prismatic layer in order to avoid changing the structure of that layer. Points are redistributed along the prism edges dynamically to resolve the boundary layer.

LEE/HENDERSON/CHOO 1992 & 1991, HENDERSON/etal 1993 base the adaptation on potential theory via sources defined from the solution monitor surface in the parameter space of the grid. HWANG/WU 1993 use the current grid as a new background grid on which to define the adaptive functions to drive the generation of a new unstructured grid. Parametric mapping was also used by SONI/YANG 1992 with NURBS representation of the grid. A related approach is movement of grid points toward a weighted center of mass as in BENSON/McRAE 1994 & 1991, BENSON/McRAE/EDWARDS 1992.

Variational principle approaches to grid adaptation, introduced in the early 80s by Brackbill and Saltzman of Los Alamos at that 0th grid conference in Nashville, generally weight measures of smoothness, orthogonality, and clustering in some manner. A number of such elements are collected in WARSI/THOMPSON 1990. BRACKBILL 1993 extends the formulation to include adaptation to a align the grid with a vector field. KNUPP 1995 also includes alignment with a given vector field.

SLATER/LIOU/HINDMAN 1995 take the time derivative of the 2D nonlinear Brackbill-Saltzman grid generation system system to produce a linear system to be solved for the grid speeds, with the grid terms evaluated from the previous time step. The grid is then obtained by point movement according to the grid speeds. A geometrical approach is taken by KODAMA 1995, setting the grid points in motion for adaptation.

Grid adaptation is meant to continuously alter the grid so as to improve the resolution of the solution being developed on the grid. The initial grid is often itself adapted to geometrical features, and perhaps also to expected physical features. Therefore it makes sense for the dynamic adaption to proceed from this initial grid and not take on the burden of continually recovering, or worse ignoring, those geometrical features. Most variational principles for adaptation have, however, been formulated between the physical space and the logically regular cartesian computational space. HAGMEIJER 1994a & 1994b addresses this concern by formulating the variational principle between the normalized computational (now parameter) space of the initial grid and the logically regular cartesian computational space. With this approach, the initial grid is recovered when the weight function is constant, instead of the equally spaced grid that is the default with a constant weight function in the conventional approach. The formulation given includes many earlier formulations, produced here by various combinations of coefficient values. In particular, a combination leading to a form of anisotropic diffusion equations is selected to allow differing adaptation in the different curvilinear directions of the initial grid.

After the idea of defining the control functions of the elliptic generation system in terms of the adaptive weight functions was introduced by Anderson in the 80s (cf. SHARPE/ANDERSON 1991), and extended by Eiseman, dynamic adaptation through the control functions of the elliptic generation system was used in Adaptive EAGLE (KIM/THOMPSON 1990, TU/THOMPSON 1990, LUONG/THOMPSON/GATLIN 1991, KIM/GATLIN 1993), the control functions being written as the sum of a geometric part (that used for the initial grid) and an adaptive part defined in terms of derivatives of the weight function. This approach also recovers the initial grid when the adaptation vanishes. Various other works, such as HALL/ZINGG 1995, since have used the control functions for adaption in a similar manner.

TAKAHASHI/EISEMAN 1994 use a variation of this approach whereby the initial grid is generated to have equal arc length spacing by varying the control functions until this is achieved. Other examples of the use of the control functions in elliptic and hyperbolic systems to control grid adaptation appear in the Barcelona and Swansea grid conference proceedings, for example SHARPE/ANDERSON 1991 for orthogonal grids with internal interfaces, and SONI 1991.

MEAKIN 1995a refines a set of cartesian background grids to accomodate moving bodies in the Chimera approach. KAO/LIOU/CHOW 1994 use the Chimera approach as an adaptive mechanism, somewhat in the spirit of the AMR (adaptive mesh refinement) work of Berger and Colella in the 80s with a hiearchy of overset cartesian grids of different levels of refinement (PEMBER/BELL/COLELLA/CRUTCHFIELD/WELCOME 1995). MOORE/FLAHERTY 1992 use a similar approach. deZEEUW/POWELL 1993 adapt a cartesian grid by further recursive subdivision.

In adaption to several solution variables, weight functions have incorporated the separate influences of the various variables in several ways beyond the simple addition of separate weight functions. WEATHERILL/SONI 1991, YANG/SONI 1992, and SONI/YANG 1992 form the weight function as a Boolean sum of solution gradient and curvature. (YANG/SONI 1992 show extremely fine resolution of a shock, with grid cells essentially collapsing into the shock.) NIEDERDRENK 1994 uses the currently largest derivative terms in magnitude in the dimensionless equations. PAO/ABDOL-HAMID 1991 apply the adaptation sequentially. MEAKIN 1995a uses the difference between the current solution value and an interpolated value of the same order. ILINCA/CAMARERO/TREPANIER/REGGIO 1995 use the difference between the computed solution and an interpolated solution to drive grid movement of an unstructured grid. PARTHASARATHY/SENGUPTA 1991 adapt an unstructured grid according to solution contours on the present grid.

Numerous measures of grid quality have been introduced. LePAPE/JACQUOTTE 1994 and JACQUOTTE 1991, and discuss the use of cell deformation relative to rectangular parallelepipeds, with a conjugate gradient solution, allowing block interfaces in structured grids to move and nodes to move on boundary surfaces. DESBOIS/JACQUOTTE 1991 use this approach for surface grids. A similar approach is followed by CABELLO/LOHNER/JACQUOTTE 1991 & 1994 for unstructured grids.

SOROKIN 1994 uses a measure of grid quality based on cell shape and size in a conjugate gradient mode to successively improve the quality of both structured and unstructured grids in 2D. SMALL 1992 uses the concept of parametric velocity to access the quality of curve/surface parametrizations.

SONI 1994 uses a NURBS representation with weighted Hermite TFI to modify structured surface grids to enhance quality. STEWART/ABOLHASSANI 1993 measure surface grid quality in terms of various curvature measures and other parameters in a graphically interactive setting. SHIRAYAMA 1991 measures the amount by which the grid fails to match analytically computed pure advection in a model problem.

EISEMAN/WANG 1992, EISEMAN 1991, LU/EISEMAN 1991 attach a control point net to the grid, allowing the grid to be interactively moved to enhance quality. CHOO/HENDERSON 1992 use the control points to couple the grid dynamically to the solution.

JENG/LIN 1995 use a least square minimization of measures of grid spacing and rate of change of spacing, localized by switching functions, to smooth an initial grid.

Finally, that dynamic grid adaption can introduce spurious dynamics into the solution in some cases was noted by SWEBY/YEE 1994.

Other work on adaptive grids and grid quality is noted in the earlier survey of THOMPSON/WEATHERILL 1993. Although grid redistribution is attractive from the standpoint of economy, and is mathematically elegant and appealing, refinement is the ultimate way.

PARALLEL IMPLEMENTATION

Block-structured grids can lend themselves naturally to distributed computing since different blocks can be assigned to different processors. Not all blocks are of the same size, however, so the assignment of blocks to processors is not likely to be one-on-one. While unstructured grids have no such obvious domain decomposition, recursive bisection can efficiently decompose a mesh with load balancing over processors.

VIDWANS/KALLINDERIS/VENKATAKRISHNAN 1994 & MINYARD/KALLINDERIS 1995 split the unstructured grid into sub-domains by input cutting planes for load balancing. Cells are then interchanged across sub-domain interfaces to maintain the balance during adaptation. A load balancing algorithm for unstructured grids based on giving/taking elements across domain boundaries was also given by LOHNER/RAMAMURTI/MARTIN 1993.

KALLINDERIS/VIDWANS 1994 & VIDWANS/KALLINDERIS 1994 define generic parallel primitives independent of the parallel architecture. The generic data representation, based on lists, is in the form of data templates which are independent of grid topology and dimensionality. Generic parallel primitives define operations on the lists, leaving architecture-specific details to implementation of these primitives on specific architectures. Adaptation trees are also included to allow for grid adaptation.

A parallel implementation of overset grids is given by BARSZCZ/WEERATUNGA/MEAKIN 1993. CHRISOCHOIDES/FOX/THOMPSON 1994 propose a problem solving environment for grid generation on clusters of machines.

BIG CODES

The 90s is the decade of the comprehensive grid code, ushered in by GRAPE, EAGLE and GRIDGEN at the end of the 80s. Then came ICEM as the first code really linked to the CAD systems. There are now quite a number of grid generation codes - in fact, nearly every establishment now seems to have at least one of its own. Some of these codes are freely available, some are proprietary, and some are commercial codes. The discussion that follows notes some that are identified in the literature by name. There are others, of course, yet without benefit of such appelation. There was occasion to discuss operational features of some of these codes above.

The NGP (National Grid Project) system of Mississippi State (A.GAITHER/K.GAITHER/JEAN/REMOTIGUE/WHITMIRE/SONI/THOMPSON/DANNENHOFFER/ WEATHERILL 1995, GAITHER 1994, REMOTIGUE 1994, THOMPSON CSE 1992) is an interactive geometry and grid generation system for block-structured, tetrahedral, and hybrid grids. The system reads CAD data via IGES and converts all surface patches to NURBS. A carpet, composed of interfacing NURBS patches, is then laid over the CAD patches to correct for gaps and overlaps. The system also has internal CAD capability for the construction or repair of surfaces. Surface grids are generated on the NURBS carpet, and can be projected onto the original CAD patches. Both the surface grids and the subsequent volume grid can be generated as block-structured via elliptic, hyperbolic, or TFI methods, or as unstructured via Delaunay or advancing front.

The ICEM-CFD system (WULF/AKDAG 1995, BERTIN/CASTIES/LORDON 1994, AKDAG/WULF 1992, BERTIN/LORDON/MOREUX 1992, delaVIUDA/DIET/RANOUX 1991) is a commercial code from ICEM CFD Engineering that was developed in Europe in the late 80s and continues to be enhanced. The system now includes block-structured grids, tetrahedral grids, and unstructured hexahedral grids. The system interfaces with numerous CAD systems and has been connected to a number of flow solvers.

The GRIDGEN system of Pointwise (STEINBRENNER/CHAWNER/FOUTS 1990, STEINBRENNER/CHAWNER/ANDERSON 1992, STEINBRENNER/CHAWNER 1992, STEINBRENNER/CHAWNER 1993, CHAWNER/STEINBRENNER 1995) is a graphically interactive block-structured system that first emerged from General Dynamics in the late 80s and continues to be enhanced. Current versions are commercial codes from Pointwise. The user constructs curves which are in turn used to build the topological surface and volume components. The user then selects curves as the boundaries of surface grids, and finally surfaces as the boundaries of volume grids (blocks). With this system, grid generation is a user-in-the-loop task. The data structure maintains the relationship among the curves, surfaces, and volumes so that changes can be propagated up or down the hiearchy automatically.

EAGLEView (REMOTIGUE/HART/STOKES 1992, JIANG/REMOTIGUE/STOKES/THOMPSON 1994, SONI/THOMPSON/STOKES/SHIH 1992) of Mississippi State incorporates the broad capabilities of EAGLE (THOMPSON 1987a & 1987b, THOMPSON/LIJEWSKI/GATLIN 1989,

GATLIN/THOMPSON/YOON/LUONG/GANAPATHIRAJU/WOLVERTON 1990) into an graphical interface that allows interactive construction with journaling. The features of this system have been outlined above.

GridPro/az3000 (EISEMAN 1995, EISEMAN/CHENG/HAUSER 1994), a commercial block-structured code of Program Development Corporation, uses a language - Topology Input Language (TIL) - to define both the surface and the block-structured grid. The language includes components (objects) that can be invoked, and therefore admits the formation of element libraries.

CFD-GEOM of CFD Research Corporation (HUFFORD/HARRAND/ PATEL/MITCHELL 1995) is an interactive geometric modeling and grid generation system for block-structured grids, tetrahedral (advancing front) grids, and hybrid grids. All elements are linked so that updates are propagated throughout the database. The geometry is NURBS-based, reads IGES files, and has some internal CAD capabilities. The system also has macro library capability.

The RAGGS system of Rockwell (WOAN/CLEVER/TAM 1995 & 1994) covers incoming CAD patches with quilts of NURBS and/or rational Bezier patches, generates surface grids from edges in space by TFI, and then projects these grids onto the quilts. The system then generates either structured or unstructered grids.

The MACGS block-structured grid generation system of McDonnell Douglas (GATZKE/MELSON 1995, LaBOZZETTA/GATZKE/ELLISON/FINFROCK/FISHER 1994, GATZKE/LaBOZZETTA/COOLEY/FINFROCK 1992, GATZKE/LaBOZZETTA/FINFROCK/JOHNSON/ROMER 1991) interfaces with CAD systems via IGES, incorporates an internal geometry modification capability, generates surface grids parametrically, and generates volume grids by TFI and elliptic means.

ENGRID is a block-structured system of the National Aerospace Lab in the Netherlands, Alenia/Gat, and Fokker (SPEKREIJSE/BOERSTOEL/VITAGLIANO/KUYVENHOVEN 1992, SPEKREIJSE/BOERSTOEL VITAGLIANO 1991, BOERSTOEL/SPEKREIJSE 1991) incorporating both TFI and elliptic generation.

The CSCMDO system (JONES/SAMAREH-ABOLHASSANI 1995, KERR/SMITH/POSENAU 1995) of CSC and NASA Langley is a block-structured volume grid generator developed to allow modifications to geometry in MDO. VOLUME (KERR/SMITH/POSENAU 1995) is another NASA Langley system that inputs surfaces from another system and generates a volume grid by transfinite interpolation.

MBGRID of Canadair (PIPERNI 1994) is a block-structured grid generation system that operates on a surface block structure formed in a CAD system. The grid generation system includes both TFI and elliptic, and is done with full-face matching among the blocks.

The GEMS block-structured grid generation system of SAMTEK-ITC in Turkey (DENER/KOC/SIRIN 1994) is based on object-oriented programming and C++ that uses case-based reasoning and reinforcement learning to capture CFD expertise. The system selects the case that is best suited for a particular geometry from among known ones.

The 3DGRAPE/AL system of NASA Ames is a block-structured grid generator that now includes the specification of arbitrary intersection angles at boundary surfaces, as well as the orthogonality pioneered by earlier versions. 3DPREP (SORENSON/McCANN 1991a & 1991b) is an interactive system that sets up input for 3DGRAPE. GRAPEVINE (SORENSON/McCANN 1992) provides an overall GUI for 3DGRAPE.

The MEGACADS block-structured grid generation system system of DLR in Germany (RONZHEIMER/BRODERSEN/RUDNIK/FINDLING/ROSSOW 1994) also uses the conventional elliptic system with control functions iteratively adjusted to achieve boundary orthogonality with specified off-boundary spacing.

The UNISG system of Fiat and Rockwell (CASELLA/VITALI/BERGAMINI/SZEMA/RAMAKRISHNAN 1994, SZEMA/etal 1993) is a block-structured grid generation system that interfaces with CAD systems via IGES files. The system uses both the conventional elliptic system and also a biharmonic system for boundary orthogonality.

The IMESH and ELGEN3 block-structured systems of DLR in Germany (HERRMANN 1991 & FINDLING/HERRMANN 1991) use the biharmonic generation system to achieve boundary orthogonality.

The GENIE++ block-structured grid generation system of Mississippi State (cf. SONI/THOMPSON/STOKES/SHIH 1992) was also introduced in the late 80s and has been continually enhanced over the years. This system uses TFI with elliptic smoothing and includes various splining methods.

The INGRID block-structured system of Deutsche Airbus (BECKER 1991) cuts local blocks out of a global mesh and fills the space with new component grids.

The TIGER system of Mississippi State (SHIH/SONI 1992, SONI/SHIH 1991, SONI/THOMPSON/STOKES/SHIH 1992, SHIH/SONI/YU/SHAUNAK 1994) is a block-structuted system specialized for turbomachinery applications. The system uses TFI with elliptic smoothing and NURBS boundary representation.

The RAPID system of NASA Langley (SMITH/BLOOR/WILSON/THOMAS 1995) is specialized to a class of airplane configurations. The CAMP system of Lockheed (SCHUSTER 1992) is a block-structured code specialized to aircraft configurations in a modular approach.

The GRID* block-structured system of ESA in Europe (HAUSER/PAAP/WONG/SPEL 1991) follows the Unix toolbox concept and consists of a collection of C routines, fairly small in size. Connectivity ond orientations are specified by an input file.

The AGPS surface geometry system of Boeing (SMIT/SU 1991 and CAPRON/SMIT 1991) is a surface preparation code than can create the input deck for EAGLE. RAMBO-4G of Aerospace (VISICH/etal 1991) also can set up an EAGLE input deck.

The SAUNA hybrid grid generation system of the Aircraft Research Association in the UK (SHAW/GEORGALA/MAY/POCOCK 1994) allows the user to remove sections of the block-structured grid, with triangular grids being then generated on the surfaces so exposed, followed by filling of the void with tetrahedral grids.

The IGG system of Virje Universiteit in Belgium (DENER/HIRSCH 1992 & DENER/HIRSCH 1991) is a block-structured system that uses TFI and elliptic generation, as well as advancing front to generate hybrid grids.

VGRID of NASA Langley and ViGYAN (PARIKH/PIRZADEH 1992 & FRINK/PRIZADEH/PARIKH 1995, earlier PRIZADEH 1992) is a tetrahedral grid generator which uses advancing front with a cartesian background grid to control resolution.

TGrid of Fluent (BLAKE/SPRAGLE 1993) is a tetrahedral grid generator based on the Delaunay approach.

The first general purpose domain connectivity codes for Chimera grids were the PEGSUS (from the Air Force AEDC) and CMPGRD (from IBM) codes in the late 80s (cf. MEAKIN 1995b), which continue to be enhanced. Advances in CMPGRD are detailed in HENSHAW/CHESSHIRE/HENDERSON 1992. Later codes are DCF3D of NASA Ames and Overset Methods (MEAKIN 1991) and BEGGAR of the Air Force Wright Lab at Eglin (BELK 1995, MAPLE/BELK 1994). The FAME system of the Defence Research Agency in the UK (ONSLOW/BLAYLOCK/ALBONE/HODGES 1994) is another.

And once there was only TOMCAT.

CONCLUSION

There are still a number of approaches being pursued in grid generation, with some combinations also. And it may be that this will continue, as Maksymiuk and colleagues (above) say in accessing grid applications at NASA Ames. Block-structured grids require fewer words of storage per grid point and can take advantage of factored and directional solvers. Tetrahedral grids work well for Euler solutions but not for Navier-Stokes solvers. Chimera grids are versatile and have some definite advantages for bodies in relative motion, but concerns arise at interfaces. Hybrid grids combine the best features of structured and unstructured grids. And cartesian grids continue to hang in there in one form or another.

The major driving factors in comprehensive grid codes must first be automation and then graphical interaction. Since design is the paramount application, the effacy of a grid code is measured primarily by the person-time it takes to generate a series of geometrically related grids for complex configurations. And the coupling with CAD systems on the front end and with solution systems on the back end must be smooth and effective. The ideal is not to make it easy for a person to generate a grid but rather to remove the person from the process - not to make it interactive, but to make it automatic.

And grid generation tools must be designed to be applied by design engineers rather than grid generation specialists.

Grid generation systems must be capable of handling very large scale variations, as occur in high Reynolds number flow, and this precludes any approach not encompassing large aspect ratio cells with good numerical properties.

Finally, there is a clear need for interaction with commercial CAD vendors. CAD codes were developed before the advance of grid generation technology and widespread application. In order to become truly effective in multidisciplinary design optimization, CAD tools must be redesigned to target computational analysis as well as tooling and material formation.

We must leave the pace car to the turbulence modelers.

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