N-Body Simulations of the Antennae

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Abstract

Collisions between galaxies can be dealt with analytically only in very specific cases. Unfortunately, the conditions that are prevalent in the bulk of galaxy interactions rarely satisfy these idealizations and so, when considering such situations, the researcher must make use of N-Body simulations to model the encounters. In general, pictorial representations of the time evolution of such encounters is desired.

In this report, I will discuss my work in this area; in particular I will concentrate on how I developed a means to convert observational and simulation data into a form that is readable by the interactive 3 dimensional visualisation tool, **Geomview**. I will also describe my work on the matching of simulation and observational data for the case of NGC 4038/9, the "Antennae", as well as the motivation for such model matching and the characteristic features of a system that are particularly suited to such fitting.

As an interesting aside, I indulged myself and present brief discussions on **The History of Mergers** and previous attempts to model the "Antennae" in **Numerical Models of NGC 4038/9**.

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1 Introduction

Until the early 1970's, the exact nature of the tail- and bridge-like features observed in many peculiar galaxies was the cause of much debate. Indeed, analysis of the discussions at the 15th IAU Symposium, "Problems of Extra-galactic Research" (1961) illustrates the then uncertain nature of the problem. Vorontsov-Vel'yaminov, well acquainted with peculiars as compiler of *The Atlas and Catalogue of Interacting Galaxies*, called for **new physics** to explain the bridges and tails he observed in his subjects; Thomas Gold advocated magnetic forces, although he noted that they would be unable to restrain matter once it was in stellar form. Fritz Zwicky confirmed that the bridges are dynamically young but contain old stars, while the Lindblads postulated that "streams of matter" drawn by tidal forces may be responsible. Thus, whilst being a subject that stimulated much debate, there was little agreement over the cause of these bridges and tails.

At this time, P'fleiderer and Siedentopf were examining whether spiral patterns in galaxies might be excited by encounters with other passing galaxies. Although their results indicated that insufficient time had passed since galaxies were formed for the numbers of spirals observed to have been generated by such encounters, their research - using computers to model the encounters - would have important consequences for the problem of bridges and tails.

In 1972, at a time when much research was directed towards understanding how these characteristic features of interacting galaxies could have formed, two brothers, Alar and Juri Toomre published a paper that would revolutionise our understanding of how interacting galaxies form bridges and tails. In **Galactic Bridges and Tails**, the Toomres presented the a basic recipe for bridge and tail building based on the tidal interaction of two galaxies. They examined 4 well known systems with well defined bridges and tails. Although highly idealised - a galaxy was modeled as a central mass surrounded a disk of massless test particles - the model encounters were able to reproduce with varying degrees of success the characteristic features of the real systems. The results for the "Antennae", one of the closest interacting systems sporting a symmetric pair of crossed tails, gave them particular pleasure.

Since then, Barnes (1988) and Bothun, Mihos and Richstone (1993) have engaged the problem of reproducing the characteristic features "Antennae". This system has been called the "Rosetta Stone" of interacting galaxies; it would be fair to say that the general feeling is that if NGC 4038/9 can be successfully modeled, then a comprehensive theory of this class of galaxies is close at hand. If such a stage is to be reached, however, then the results of modeled encounters must match those of observations. In a recent review, Barnes (1998) outlined four key features of the "Antennae" which have thus far eluded attempts to model them. It should be clear that model matching, and in parallel, the visualisation of the results of simulations are of vital importance if a clear understanding of galaxy interactions is ever to be achieved. In this report, I shall outline the fruits of my Summer's work in this particular area.

In section 2 I present a brief account of how our understanding of collisions between galaxies has evolved over the course of this century. From the earliest postulations of Lundmark and Lindblad to the ingenuity of Holmberg and the wild theorizing of Zwicky to the breakthrough computer experiments of the Toomre brothers, the history of the subject is both colourful and invigorating, and in my opinion, worthy of some discussion.

Section 3 deals with previous attempts to model NGC 4038/9 numerically; in particular, I consider the 1972 effort of Toomre and Toomre which relies on a

restricted 3 body code, and Barnes' 1988 attempt which utilises a 3 dimensional fully self consistent N-Body code. I also briefly discuss a recent paper by Mihos, Richstone and Bothun (1993) on star formation rates in NGC 4038/9, and indicate areas in which future models must improve.
Section 4 is concerned with model matching process. For any physical model of the Antennae to be considered plausible, it must reproduce the observed features of the system. I discuss the essential elements of any model matching scheme and part of my Summer's work.
Visualisation of Data, the topic of section 5, reflects the bulk of my Summer's work; in particular, it deals with the 3 dimensional representation of our data. After due consideration, the highly interactive 3D visualisation package **Geomview** was chosen as the viewing tool. I briefly discuss the development of software that processes both observational and simulation data into a form suitable for 3D viewing; the hopes for future development of this software; and the related topic of automating the model matching process in an efficient and flexible way.

2 A History of Mergers

Recent observations of the Hubble Deep Field (Abraham et al., 1996) have shown that the fraction of peculiar objects seen is significantly higher than it is among nearby galaxies. A sizable fraction of QSO hosts appear to be ongoing mergers, as originally envisioned. On a more fundamental level, mergers are thought to play an important role in structure formation in the early matter dominated epoch of the Universe.
However, mergers are not confined to exotic circumstances in history; if we look at the local Universe, there are numerous examples of disturbed galaxies that quite obviously point to galaxy interactions. Such a view was not always held; for many years, right up until the early 1970's, many held the opinion that simple *gravity* acting on stars could not produce the characteristic features - bridges and tails being the prime examples - of the class of peculiar galaxies.

2.1 The Hubble Sequence

In 1920, a Great Debate raged between Harlow Shapley and Heber Curtis; **what was the scale of the Universe?**. Considering the "spiral nebulae", what we now know to be external galaxies, Shapley argued that these were merely nearby gas clouds in a Universe that existed wholly within our own Galaxy. Curtis disagreed; he expounded the view that the Sun was but a member of a small Galaxy of which there were many.
The true nature of our Galaxy and the Universe was resolved by Edwin Hubble.

Using the 100 m Hooker telescope he was able to gauge the distance to Cepheids in M31, the Andromeda Galaxy; this distance was greater than that proposed by Shapley for the dimensions of our Galaxy and thus M31 must lie beyond its boundaries, a galaxy in its own right.
Hubble is perhaps better known for his observations which demonstrated that the Universe is expanding (borne out in the by now infamous Hubble Law), but he was also responsible for another important development of extragalactic astronomy - the **Hubble Sequence**. It should not be surprising that Hubble spent many years surveying thousands of galaxies, and during the course of his work, he noticed a trend - galaxies could be ordered into a sequence based on their morphology, the so called Hubble Sequence.
On the left hand side of the sequence, which is commonly called a Tuning Fork diagram, we have the ellipticals which range from E0 up to E7 based on their ellipticity. E0s are spherical and ball like while an E7 is shaped like a rugby ball. At the vertex we have the S0s, lenticulars - galaxies which have disks like spirals but unlike spirals are bulge dominated. Then we branch out into the spirals, Sa, Sb and Sc and the barred spirals, SBa, SBb and SBc.
The obvious question to ask is why the dichotomy of shapes among bulge dominated versus disk dominated galaxies? This was a problem of nature versus nurture - initial guidance was sought in the formation of galaxies, and indeed, the ELS (Eggen, Lynden-Bell, Sandage) hypothesis seemed to offer a solution. Stars in ellipticals formed far earlier and more quickly during the initial collapse of a primordial gas cloud than their counterparts in spirals. However, this now introduced the question, why should this be so? It is at this point that the importance of galaxy mergers becomes clear.

2.2 Early References to Mergers : Lundmark (1926) and Lindblad (1926)

The first studies of pairs of interacting galaxies was undertaken in the early 1920's. Knut Lundmark, then at Upsaala Observatory in Sweden, carried out investigations of "double nebulae". (1920, 1926, 1927) Assuming that both of the galaxies are at the same distance from the observer, Lundmark deduced the relative properties such as size and luminosity of the different morphological types of nebulae. Based on this research, he was able to conclude that given the large sizes of the "nebulae" relative to their separations in space, "collisions or encounters must be rather common among these objects.
Lindblad (1926) further theorized that "sharp encounters between nebulae...must be considered as highly inelastic and must tend to convert translational (i.e. orbtial) into rotational (i.e. internal) kinetic energy. An encounter of this kind may even lead to a fusion of the respective bodies."

2.3 Holmberg (1941)

Erik Holmberg was interested in the clustering tendencies of galaxies; galaxies arise in a variety of locations. A few percent can be found in clusters of hundreds; a still greater fraction can be found in groups of tens. Our own Galaxy and M31 are both part of a group of galaxies called the Local Group. In particular, Holmberg wanted to explain the origins of these groups and clusters, and the mechanism he had in mind was the mutual tidal capture of galaxies during initial hyperbolic passages. Initially the galaxies approach each other with sufficient energy to escape to infinity but lose energy during the encounter and thus become bound. By assuming a uniform distribution of galaxies, each with a peculiar velocity of a few hundred kilometers per second, Holmberg envisaged the gradual accumulation of galaxies into groups and clusters.

Unfortunately for Holmberg, there is a fundamental problem with this hypothesis; when the probability for an encounter is estimated, we find that only one galaxy in ten thousand will have had sufficient time to be tidally captured during the lifetime of the Universe, quite at odds with observations.

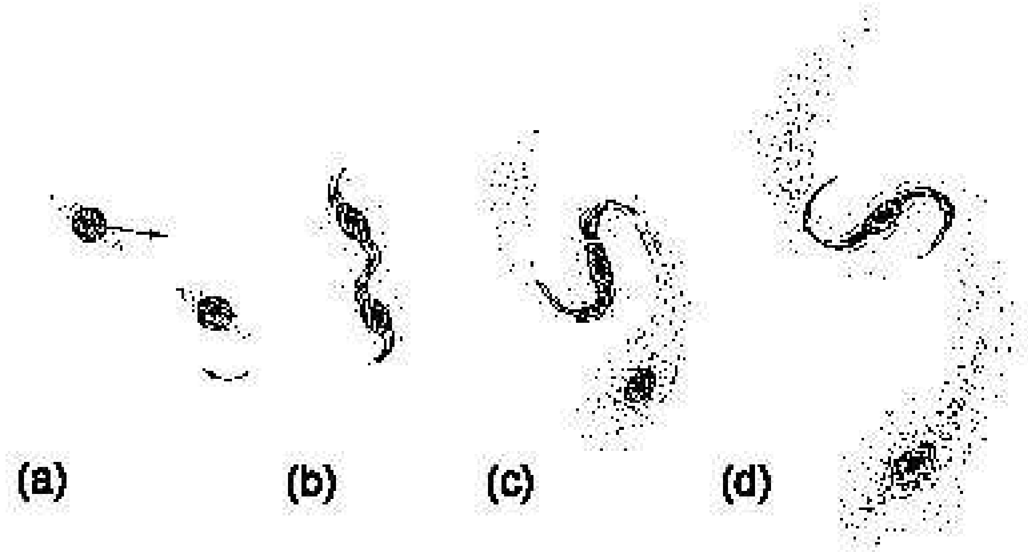
Despite this, it is interesting to follow Holmberg's experiments of tidal capture of galaxies during close encounters. These were numerical experiments in which each galaxy was modeled as 37 mass points arranged in concentric circles traveling around a common centre. What perhaps was most ingenious about this arrangement was that the mass points were represented by light bulbs! By using the inverse square behaviour of light, Holmberg had uncovered a method to mimic gravitational forces - this was the most computationally intensive part of the problem. Photocells were used to detect the magnitude and direction of the "gravitational force", i.e. the light, and so it was possible to map the trajectories of the mass points by graphical integration.

Holmberg simulated planar encounters between disk galaxies using this technique; he was able to estimate the efficiency of tidal capture for a variety of approach velocities, rotations and minimum separations. Whatsmore he correctly noted that the maximum tidal distortion occurs **after** the passage of the interloper through pericenter. However, he did not report any problems with bar instabilities, something which should have plagued such a cold disk, and he also noted that tidal capture was most efficient during retrograde passages when the disks counter-rotated in an opposite sense to their orbital motion. As noted in Barnes (1996), this is "curious".

In addition to the hyperbolic passages, Holmberg did investigate parabolic encounters and used them to illustrate tidal deformations, but because of the number of mass points involved and the approximations made, felt that this was not sufficient for a detailed study of tidal response. Hence an opportunity was missed to uncover the tidal origins of bridges and tails.

2.4 Zwicky (1953,56)

Fritz Zwicky was the first to start systematically photographing peculiar galaxies using his 18 inch Schmidt camera at Palomar. Using these images, he quickly concluded that many of the narrow filaments that he observed must be due to tides stemming from gravitational interactions. In a 1953 issue of *Physics Today*, he described these filaments as tides and countertides and furthermore, correctly deduced that the narrowest of them must be sheets of matter seen edge on; furthermore, he emphasized that much of the visible matter in the bridges and tails must consist of stars. Shown below is one of his sketches - "the possible formation of an intergalactic bridge between two galaxies passing each other".



In the sketch, Zwicky considers the possible bridge formation between two interacting galaxies; the resulting configuration closely resembles Arp 96. Note that the lower galaxy in instances (a) and (b) becomes the upper galaxy in instances (c) and (d).

2.5 Vorontsov-Vel'yaminov (1959) and Arp (1966)

Vorontsov-Vel'yaminov published **The Atlas and Catalogue of Interacting Galaxies** in 1959. A compilation of interacting galaxies found in the Palomar Sky Survey and the Crimean Station of the Institute, *The Atlas...* was a record of fragmenting galaxies according to Vorontsov-Vel'yaminov, a theory proposed by Ambartsumyan in 1958.
Inspired by both Zwicky's sketches and faint images of peculiar and distorted galaxies, such as those of Vorontsov Velyaminov, Halton Arp spent four years photographing many such objects with the Palomar 200 inch. He believed that

"the peculiarities...represent perturbations, deformations and interactions which should enable us to analyze the nature of real galaxies which we observe and which are too remote to experiment on directly". In 1966, he published his Atlas of Peculiar Galaxies, containing high resolution images of 338 systems .

2.6 Toomre and Toomre (1972)

During the 1960's, Pfleiderer and Siedentopf investigated how spiral patterns in disk galaxies could be excited by gravitational interactions between disk galaxies and concluded that chance encounters between field galaxies are not sufficiently common enough to produce the observed population of spirals. However, they did produce, albeit in passing, the first plots of tail and bridge building.
This was followed in the early 1970's by a spate of papers, but one in particular stands out. **Galactic Bridges and Tails** by Toomre and Toomre (1972) is seen as many as the seminal paper in the field of galaxy interactions and mergers. Although it was not unusual at this time for a paper to be published that dealt with computer modeling of interacting galaxies, the publication of TT's paper was seen by many as a key turning point in the theory of interacting galaxies, triggering a true paradigm shift in the field. As will be highlighted in the next section, **Galactic Bridges and Tails** clearly established that bridges and tails - which for so long were the source of much heated debate and disagreement - were gravitational in nature. The paper comprehensively offered a very plausible and natural means to produce these characteristic features of interacting galaxies and indeed, through their discussion of related phenomena in the final section, the Toomres inspired a burst of new research. In particular, the discussion, *Stoking the Furnace*, preempted Larson&Tinsley's 1978 paper which showed the connection between starbursts and the merging of galaxies.

3 Numerical Models of NGC4038/9

There have been several attempts to model the "Antennae" in the literature. I will, however, concentrate this discussion on Toomre and Toomre's 1972 paper, **Galactic Bridges and Tails** and Barnes' 1988 paper, **Encounters of Disk/Halo Galaxies**.
At the end of the main discussion, I will briefly discuss some of the observations that must be satisfied if the models are to be considered successful reconstructions.
Toomre and Toomre's 1972 paper is seen by many as the seminal work in this field, triggering a paradigm shift and establishing mergers and tidal interactions as respectable subjects for theoretical inquiry. Although there were several papers in the literature dealing with interacting galaxies at that time and despite the fact that their modeling of galaxies as central masses surrounded by disks of test particles was hardly novel, there were many virtues to the Toomres' work:

- their clear establishment of the necessary conditions for interactions to occur, in particular, an appreciation for the importance of bound encounters.
- their lucid descriptions of bridge and tail making
- their analysis and reconstruction of several well known interacting systems
- their discussion of merger related phenomena which preempted observations made several years later.

Barnes' paper, published 16 years after the Toomres' attempt, was the first to model interacting galaxies as fully 3 dimensional N-Body entities whose equations of motion were integrated in a self consistent manner. An important and telling addition to the simulation's armory was the presence of a massive dark halo; this would have an important effect on the evolution of the merger.

3.1 Toomre and Toomre, 1972

In **Galactic Bridges and Tails**, Toomre and Toomre (hereafter, TT) considered encounters between pairs of galaxies on parabolic orbits; each galaxy was idealized as just a disk of noninteracting test particles initially in orbit about a central mass points. As a result, all explicit self gravity of the disk was neglected; this was justified on two grounds:

- the self attraction of the outer part of a disk is, by definition, small. Hence, by neglecting self gravity the main qualitative conclusions are unlikely to be affected.
- by relying on test particles as tracers it was hoped to make clear the kinematic nature of the observed filamentary structures.

TT modeled 4 interacting systems - Arp 295, M51, NGC 4676 and NGC 4038/9 - but it was their reconstuction of the "Antennae" which gave them "the most pleasure". This stemmed from prior concerns regarding whether "it was possible to obtain seemingly crossed tails from tidal interactions".
In section IV of TT, *Survey of Tails*, it is noted that "proper tail making in the sense of escape to infinity of particles from the antitidal side of a victim disk requires the perturbing mass to be at least comparable to the perturbed". Hence, if we observe an interacting system with two prominent tidal tails emanating from both disks of both galaxies then we can conclude that the masses involved were comparable and that the separation at periapse was small. With this assumption in mind, a mass ratio of exactly unity was assumed in the survey of 3 dimensional tails. This survey was of particular importance for analysis of NGC 4038/9, and in particular figure 18 of this section, shown below, plays a

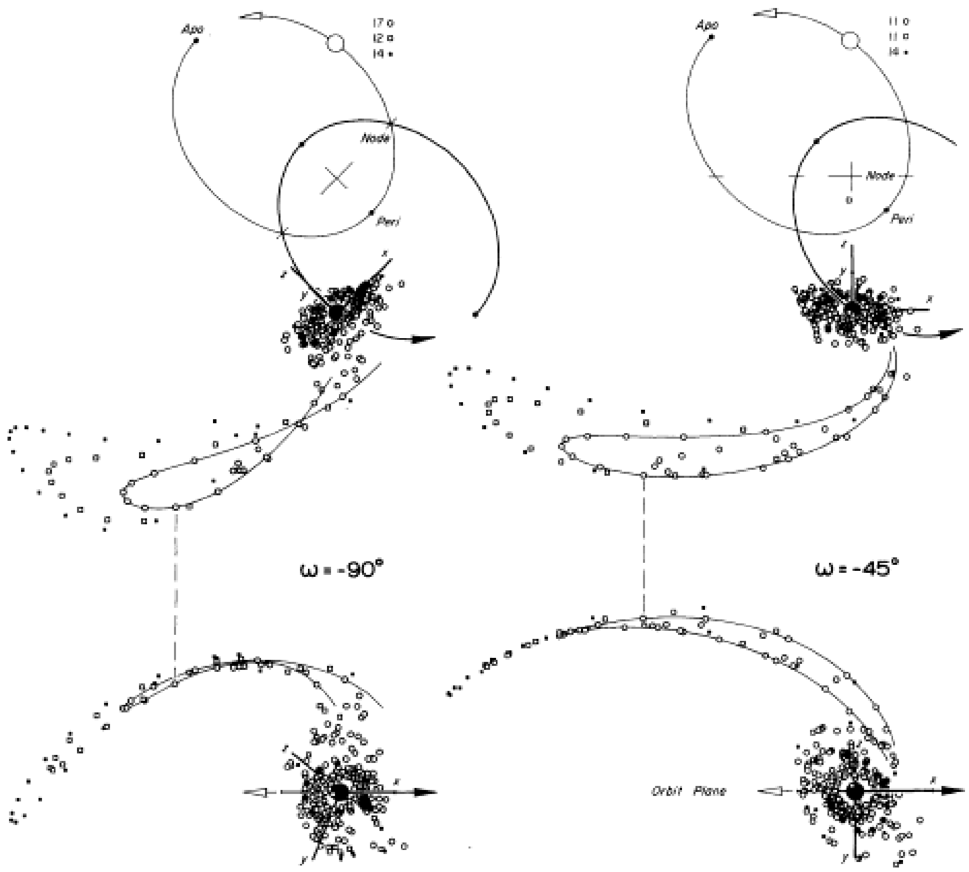


Figure 1: Figure 18 on page 623 of **Galactic Bridges and Tails**. This is part of the tail survey; in this case, the ellipticity was $e \approx 0.6$ for equal mass passages of fixed inclination $i = 60^o$ but with different orbital arguments of $\omega = -90^o, -45^o, 0^o$ and45^o. The viewing time is t=6.086 in their units, corresponding to 135^o of orbit travel since pericenter. The viewing angles are normal and edge on to the orbit plane; in this case, the edge on views are from directions which exactly superpose the centers of victim and satellite.

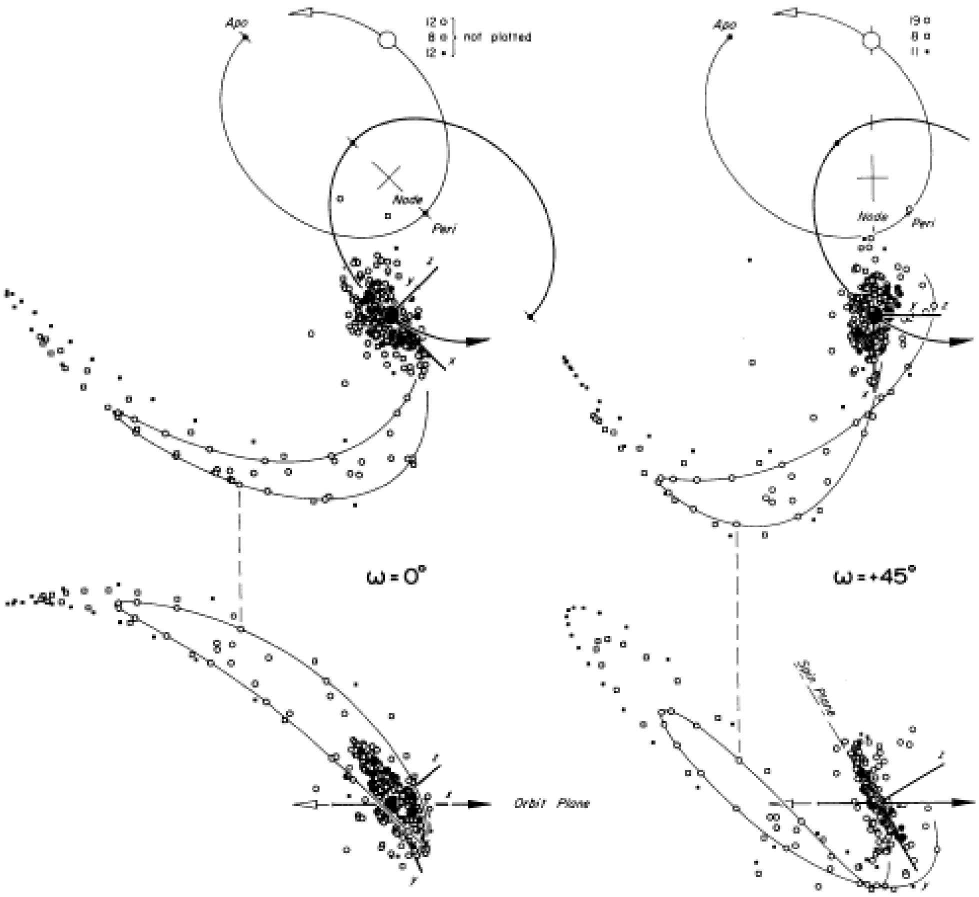


Figure 2: Figure 18 on page 624 of **Galactic Bridges and Tails**.

central theme.

TT observed that if every bare companion carried an $i = 60^o$ tail of its own, chosen from amongst the four possibilities after a 180^o visual rotation about the axis normal to the orbital plane, that no tail crossings were to be found in any view that was roughly perpendicular to the orbits. In addition to this, they were able to exclude all other views from near the great circle normal to the line connecting the masses; this was because of the precondition that no part of one tail could be much closer to the other than the distance between the hulks themselves.
Views from along the connecting line, however, produce a pair of crossed tails which TT compare to a "pair of symmetric gull wings". In this case, they utilised the $\omega = -45^o$ tail in figure 18 together with its identical twin attached to the perturbing mass. Similar results are possible for both the $\omega = -90^o$ and $\omega = 0^o$ cases, and almost the same for either case partnered with $\omega = -45^o$ ribbon. The result is illustrated in figure 23 of TT, as shown.
TT chose the precise orbital parameters used in figure 23 to produce a result in accord with their 1971 NGC 4038/9 movie.
The forces from each massive body were softened gradually at close range by varying the potential at small radius as:

$$\Phi \approx -\frac{GM}{\sqrt{r^2 + a^2}}$$

where $a = 0.2R_{min}$ as opposed to the standard $\Phi = -GM/r$. This gravity softening was essential in the mimicking of the mass distribution; if neglected, too many of the near side particles would have been extracted from both of the disks. In addition, this gravity softening facilitated further thinning of the tails.
Whilst the models successfully reproduced the hallmark crossed tails of the "Antennae", TT noted several deficiencies:

1. the real tails are unequal in length.

2. the actual NGC 4038 tail is more curved than in the model.

3. the rotation of the real hulks seem to be such that their adjacent ends approach and recede alike whereas the opposite holds true for the models.

In an attempt to remedy these shortcomings, TT made three suggestions:

- unequal tail length (objection 1) can be achieved by introducing slight inequalities in either the masses, inclinations or the initial outer radii.

- the second objection would seem to suggest that a second encounter will occur.

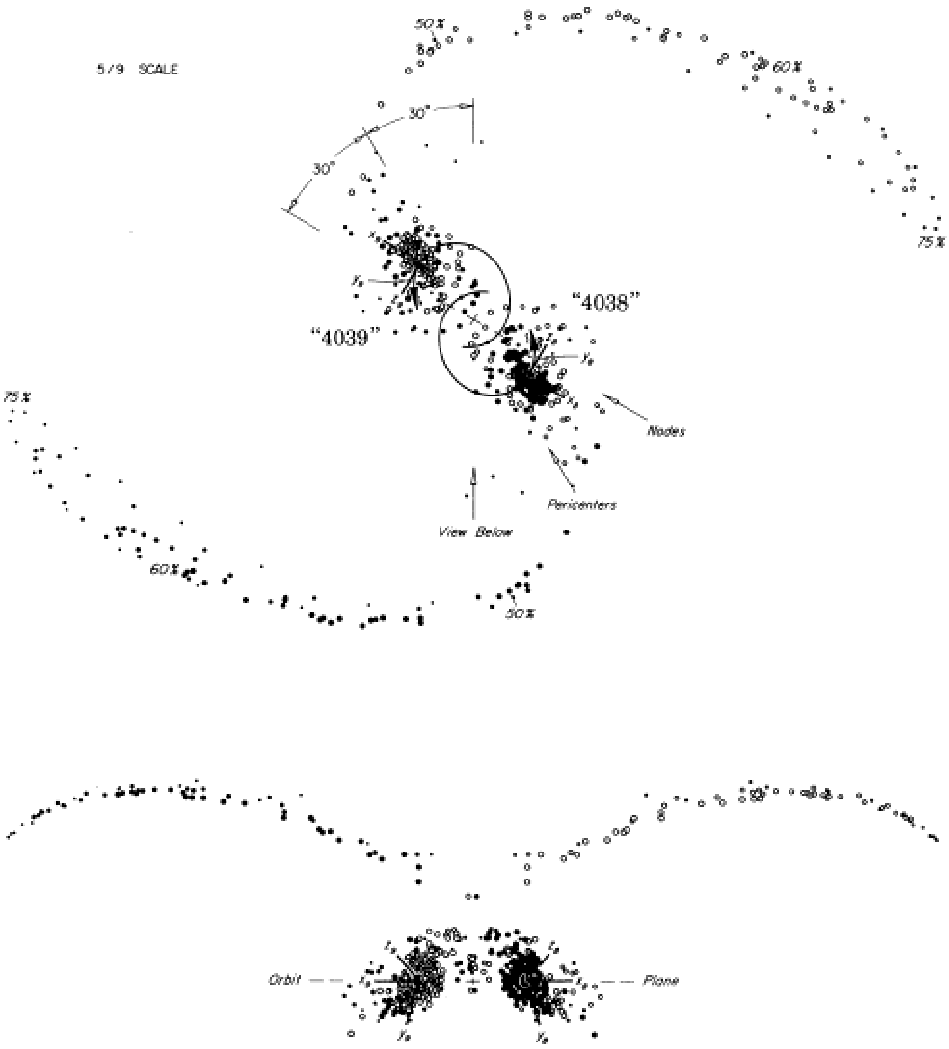


Figure 3: Figure 23 of **Galactic Bridges and Tails**. In this instance we see two identical disks of radius 0.75 R_{min} which have undergone an $e \approx 0.5$ encounter with orbit angles $i_8 = i_9 = 60^o$ and argument at pericenter $\omega_8 = \omega_9 = -30^o$ that appeared the same to both. The subscripts refer to the galaxies NGC 4038 and NGC 4039 respectively. The upper view is exactly normal to the orbit plane, while the lower view is edge on to the orbit plane with a viewing direction 30^o from the line connecting the two pericenters. The viewing time is at t=15 in their units, just slightly past apocenter.

- the third objection, by far the most serious, requires a substantial change of at least the argument ω_θ from $-30^o \rightarrow -90^o$ as well as a further reduction in the longitude of viewing.

Despite the shortcomings, the Toomres captured the essence of the Antennae with a simplified 3-body model, and as they indicated, if further progress was to be made then a full N-Body self consistent code was necessary.

3.2 Barnes, 1988

In **Encounters between Disk/Halo Galaxies**, Barnes used prototype bulge/disk/halo model galaxies. These models consisted of a central bulge, a thin rotating disk and an optional spherical extended halo. The exact details of the simulated encounter which would produce the observed features of NGC 4038/9 followed those of Toomre and Toomre; the initial conditions corresponded closely to those used in **Galactic Bridges and Tails**, although some modifications were necessary to account for the presence of the massive dark halo.
The main characteristics of the model galaxies were as follows:

Mass Ratio of Components	1:3:16
Total Mass of Components	$M_B + M_D + M_H = 1.25$
Inverse Scale Length of Exponential Disk	$\alpha = 12$
Circular orbital period at radius $r = 3/\alpha$	$t_{orbit} = 0.93$

All these quantities were measured in arbitrary units with $G = 1$. Scaling to our galaxy, these numbers correspond to a length of 40 kpc, a time of 250Myrs and a mass of $2.2 \times 10^{11} M$.
The galaxies were started on elliptical orbits with an eccentricity of e=0.5; their pericentric separation was $r_p = 0.5$ and the time to pericentre was $t_p = 1.0$. Both galaxies were inclined at $i = 60^o$ to the orbital plane with a pericentric argument of $\omega = -30^o$.
These particular initial conditions will lead to a slow symmetric prograde encounter with the two disks inclined so as to sling tidal tails high above the orbital plane where they will eventually be seen in projection crossing each other. The configuration used is shown in figure 4.

Whereas Toomre and Toomre's test particle model galaxies followed Keplerian trajectories, the orbits of Barnes' self consistent model galaxies quickly decayed. The tidal coupling of orbital to internal motion was so effective that the relative orbit decayed in less than one initial orbital period. This was due to the presence of the massive dark halo which effectively soaked up the energy and angular momentum, as shown previously by van Albada and van Gorkum. Barnes noted that at the time when TT's model most closely matched observations, his models had already merged. However, his models do produce a configuration that

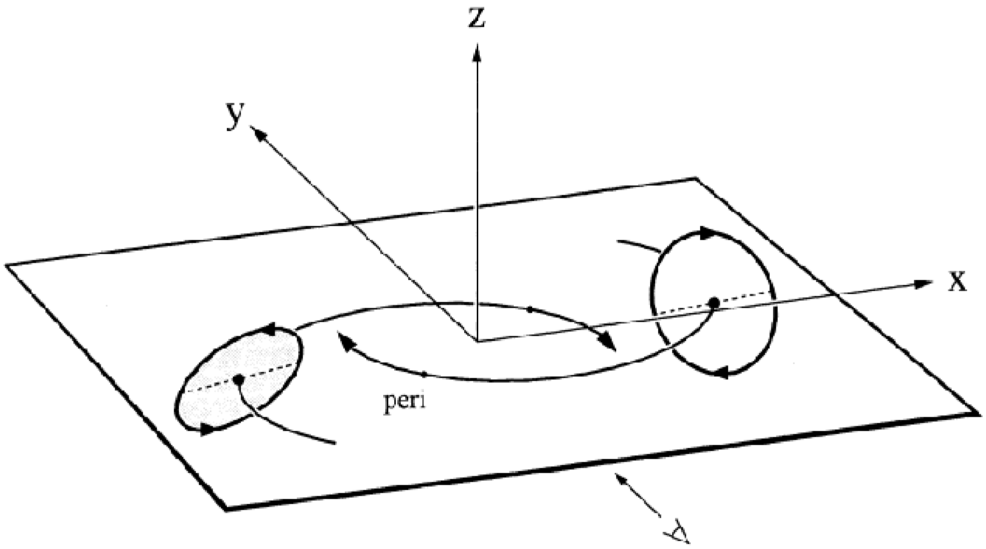


Figure 4: Figure 1 of **Encounters of Disk/Halo Galaxies**, illustrating the geometry of the encounter.

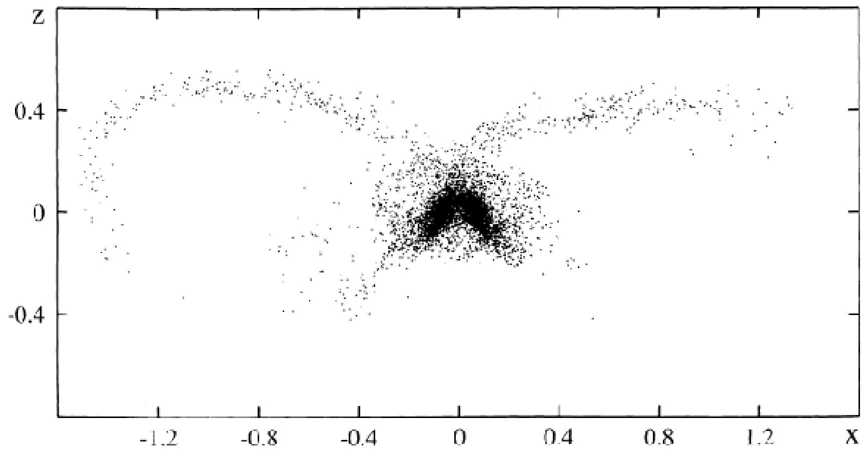


Figure 5: Figure 2 of **Encounters of Disk/Halo Galaxies**, showing the resulting configuration.

resembled observations but at *a much earlier time* - t=1.8 in his arbitrary time units, corresponding to roughly one quarter of the initial orbital period after pericentre.
Further analysis of the encounter revealed several interesting features:

- the interaction slewed the inner galactic disks by $\sim 70^o$ counterclockwise, almost edge on to our line of sight, indicating the presence of powerful torques on the disks during the encounter.

- distinct peaks in the dark matter distribution were observed to coincide with the luminous tails, "like a dark, distended body surrounding a luminous spine".

- the visible tails were confined within the halo; this is a consequence of the dark matter, which initially shared phase space with the luminous matter, tagging along to the present stage.

- the more curving left hand tail of the model matches closely the appearance of the south western tail as revealed in both deep optical images (Schweizer, 1978) and high resolution HI mapping (Van der Hulst, 1979).

- Barnes was keen to stress that the asymmetry between the two tails was not due to any macroscopic asymmetry in the initial conditions [1] but was instead due to $\sqrt{N}$ fluctuations in the galaxies which are swing amplified by the disk and sheared out by tidal forces during the encounter, thus further populating one of the resulting tidal arms.

Reviewing this particular simulation, Barnes considered both the positive and negative aspects of the result; the model encounter successfully reproduced:

- the narrowness of the tidal tails. This demonstrated the requirement for relatively cold disks. Previous attempts to self consistently model encounters of this kind, such as those of Negroponte (1987), produced stubby tails, clearly at odds with observation.

- the proximity of the hulks. This is a distinct improvement on TT's model; although TT foresaw the importance of orbital decay due to tidal friction, they certainly could not have anticipated the rapidity of the decay. By following the bulges (which trace the dynamical centres of the galaxies) Barnes was able to observe that these bulges barely separated after pericentre, plunging back together after one third of an orbiral revolution.

However, the model result was not without its shortcomings:

- The model galaxies, as shown in figure 5, are approaching one another along the line of sight with velocities comparable to the circular velocity

[1] Indeed, the encounter itself was symmetric.

of each disk. However, studies in HII (Rubin, Ford and D'Odorico, 1970) and HI (Mahony *et al*) indicate only a small line of sight difference - $\sim 40kms^{-1}$. Thus the model fails to match the observed kinematics of the main hulks.

- Conceptually there are problems associated with the very existence of this e=0.5 orbit. The orbital period for such an encounter is *longer* than the Hubble time! Due consideration would seem to suggest that the galaxies experienced a close parabolic encounter - but such encounters do not result in configurations such as the one observed in the Antennae.

In conclusion, Barnes noted that the model of NGC 4038/9 came *subjectively* close to matching the appearance of the Antennae; based on this observation, it was felt, with some confidence, that the basic elements of the encounter were correct. He did caution, however, that the quality of the match was somewhat enhanced by the presence of *chance fluctuations* which could grow to macroscopic proportions at the right time and place to produce asymmetric tails - and so it would be **neither possible to infer precise properties of the progenitors nor to establish the uniqueness of a solution**.

3.3 Star Formation Rates in the "Antennae"

In their 1993 paper, Mihos, Richstone and Bothun considered models of NGC 4038/9 directly based on those used by Barnes in **Encounters of Disk/Halo Galaxies**, but with star formation rates in mind.. They tried to match the observed SFR with the model SFR by examining the spatial distribution of Hα and CO, but discovered that the models predicted that the nuclear regions should carry the majority of the star formation and ISM mass in the system. Based on observations, the model should have demonstrated the SFR and CO emission evenly divided between the nuclear and overlap regions.

3.4 Future Directions

As is clear from the previous discussions, while NGC 4038/9 has been modeled with some success, the simulated encounters have failed to reproduce some of the key characteristics of the system. In his 1998 review of galaxy interactions, Josh Barnes outlined four key elements that any improved model of the Antennae must include:

- Matching the observed velocity field - radial velocities of the two galaxies differ by only 40 kms^{-1}, much lower than those produced in previous models.

- Reconciling the adopted orbit with cosmological expectations - whereas previous simulations adopted elliptical (e$\sim$ 0.6) orbits, parabolic orbits would seem to be more plausible.

- Reproducing the gas rich ring in NGC 4038 - this ring is clearly visible in both the mid-IR and HI maps, and contains many young star clusters.
- Explaining the "overlap region" - this dusty region is brighter than either disk in mid-IR wavebands according to recent ISO observations. (Mirabel et al., 1998)

4 Model Matching

If a model is to be considered a successful representation of a physical system, it must reproduce the essential features of the system as gauged by observations. In the case of interacting galaxies, this reduces to matching the characteristic morphology and kinematics, but it is by no means a simple task.
As outlined in the previous section, there are several parameters which govern the evolution of an interacting pair of galaxies - the mass ratio of the pair, the inclination of their relative orbits, the pericentric argument, the ellipticity of the orbits and the viewing angle to name but a few. Subtle changes in a single parameter may have a significant effect on the morphology and kinematics of the observed pair. Furthermore, it is possible that no single set of initial conditions uniquely determine the final outcome (Barnes, 1988).
With these significant factors in mind, it is clear that model matching is a potentially daunting task. However, by making some plausible assumptions and deciding to work with carefully chosen characteristics of the system, it is possible to simplify the process somewhat.
When we set out to match tailed galaxies, our sample is already predefined - spiral galaxies which possess dynamically cold gas rich disks. As described above, Barnes noted in his 1988 paper that such dynamically cold disks are essential if the characteristic features of tidal interactions are to be reproduced. Furthermore, it is a well known observational fact that spirals have copious amounts of HI in their disks and that this neutral hydrogen extends out to approximately twice the luminous radius of a galaxy. This key fact coupled with the 21cm spectral line of HI which freely exhibits a Doppler shift in response to its motion offer us an effective **tracer**. Such a tracer reveals not only the spatial structure of bridges and tails but also the line of sight velocities. This information is vital.
In modeling encounters between galaxies, how the galaxy is represented can play a important role in how the interaction evolves. As Barnes (1988) noted, the inclusion of the massive dark halo in his fully N-body self consistent BDH encounter had a profound effect on the merging time when compared to Toomre and Toomre's 3 body test particle encounter. (This demonstrates the importance of the dark halo for tidal friction and orbit decay.) Any *recipe* for model matching that is adopted must target characteristic features which are model independent.

For the model matching, I made extensive use of John's **Identikit** display package; this gives 3 separate projections - X-Y, Vz-Y and X-Vz- of the data under consideration, where X,Y and Z are the standard spatial coordinates and Vz is the line of sight velocity. The user can perform rotations about the spatial axes as well as scalings (both radial and velocity) of the model data compared to preloaded HI observational data.
During the early stages of the fitting process, I used alignment of the bulges as an initial guide towards a best fit; this seemed reasonable since the bulges track the dynamical centres of the galaxies. However, I soon revised the technique; the bulges **do** track the dynamical centres but their exact behaviour is uncertain under different kinds of galaxy models. Thus, I decided to simply concentrate on using the tails to guide the matching process.
Although I identified several lines of enquiry whose results would prove useful for future model fitting, both circumstances and time hampered any efforts to pursue them. In particular, I had hoped to investigate how the inclination of the disks during encounter affected results in terms of model dependency and also how changes in the respective orbital inclinations of the individual galaxies would change the results of the encounter.
Essentially, the primary purpose of my model matching efforts was not so much to identify a best fit - unlikely given the size of the parameter space - but to identify steps in the process which would lend themselves to automation. Discussion with John would seem to indicate that this primary goal was achieved.

5 Visualization of Data

5.1 Visualization and N-Body Simulations

One of the key aspects of my Summer's work was to develop software which would facilitate 3 dimensional visualisation of both model and observational data.
The very nature of the problem - modeling interactions between galaxies - is one played in a 7 dimensional parameter space of which only 3 of the dimensions - X, Y and Vz - are observable. What we observe is sensitive not only to the intrinsic physical parameters of the system, such as the mass ratio of the galaxies, but also to our viewing angle. Indeed Zwicky, in 1953, realised the importance of projection effects on what observe in his analysis of M51, noting that the narrowest of the filaments observed may be broad sheets of matter seen nearly edge on. It is not difficult to imagine a range of initial orbital parameters producing results which resemble the Antennae as we observe them today. This particular point was emphasized in **Encounters between Disk/Halo Galaxies**(Barnes, 1988).
Primarily, my intention was to build a programme that would allow the user to

view and manipulate, in effect, to get a physical picture of the data in a three dimensional form, before moving on to carry out more quantitative analyses using John's existing software.
Several options were considered - IDL, Java, VRML and the final choice, Geomview. Geomview is an interactive three dimensional visualisation tool that was developed by the now inactive Geometry Centre. As a means of visualisation, it is particularly user friendly and fulfilled all out criteria for processing speed and ease of use. The range of actions available to the user - rotations, translations, zoom in and out - are carried out by a simple point, click and drag. The object can be simultaneously viewed from several camera locations and the user mayb observe how the view changes from different perspectives.
The next task was to develop a programme which could take our existing data and convert it into a format which could be read by Geomview. I decided to use C for the writing of this programme because it is reasonable to expect that most users will have some proficiency in this particular language, thus allowing them to modify the programme if necessary, and also because I wished the programme to be integrated into exisiting software which is written in C.
The problem in hand reduced to reading in data which may exist in a variety of formats and writing this data to file in a form that would give a meaningful physical representation of the results. The first part of the problem was dealt with relative ease - given the structure of the data files which were to be read, I could simply tailor a specific function to read the required data from the file. The second part of the problem required a little more thought, but serendipity showed her hand and it was discovered that by using the OOGL VECT object file format, it was possible to get a particle representation of the data.

5.2 Sim2Oogl - A Snap, Zeno and P File Conversion Programme

With this information, writing the programme was quite straightforward; invoked from the command line, the programme which is called **sim2oogl** requires the name of the data file to be converted, the format of the data file and the type of output desired.

- the format of the file : this refers to the structure of the file - it can be SNAP/Tipsy, Zeno or P.
  - Tipsy files are readable by the Tipsy data visualisation package; this allows results of N-Body simulations to be quickly displayed and analysed.
  - Zeno files are produced by Josh Barnes Zeno N-Body simulation package.
  - P files are simple ascii data files

- the type of output desired : this rather self evidently refers to the form of Geomview readable output that is produced by the programme. The user can choose one of:
  - position coordinates (X-Y-Z)
  - velocity coordinates (Vx-Vy-Vz)
  - position (X-Y) with line of sight velocity (Vz)
  - position (X-Y-Z) with velocity vectors (Vx-Vy-Vz)
  - all of the above

Additional options are available - the user can define the number of particles in the disks and halo as well the number of galaxies involved. The default assumes two galaxies without halos and each disk containing N/2 particles, where N is the total number of particles involved in the encounter.
Since Geomview is being used to display our data, I decided to further develop sim2oogl into an external module which can be used in tandem with the command line version of the programme. This module is called **Sim2Oogl** and it offers the user a GUI, built using the Tk/Tcl toolkit and scripting language, and invoked from within Geomview. The GUI extends the usability of sim2oogl, allowing the user to carry out a batch conversion of data files in addition to allowing files to be viewed once they have been converted.
The Tk GUI is built on top of the basic command line version of sim2oogl; the programme's function which handles input and output can be developed into a dynamically loadable extension that can be loaded into the Tcl interpreter using the *load* command. In principle, this is possible by working with Tk/Tcl's collection of C libraries, but a somewhat easier route was taken by using a programme called SWIG. SWIG requires an interface file in which the C functions to be used are declared as external objects; when invoked, SWIG then produces a wrapper file that is compiled and linked with the rest of the programme. In doing so, we get the dynamically loadable extension that can then be loaded into the Tcl script. Thus we have a means for exchanging information between the user interface and the basic conversion programme, as desired.
A comprehensive website - *http://www.cv.nrao.edu/˜cpower/Sim2Oogl* - **Sim2Oogl1.0 in a Nutshell** was prepared (and mirrored in the packaged documentation) for user support. Further modifications of the programme will be posted to this website as they come to fruition.

5.3 Sim2Oogl as a Scientific Tool

Sim2Oogl was initially developed with aspirations of serious quantitative analysis in mind; however, after some time it was noted that it's main developer, Geometry Centre, has been inactive since early 1998 and thus active support is no longer available. Both John and myself had planned to contact groups using

Geomview for 3-D visualisation of N-Body data in the hope that their experiences would help guide our usage of Geomview. Could John's existing software, which displayed different aspects of the data in phase space, be superceded by a programme which used Geomview to display this information? This question was left unanswered, but my feeling is that it may be possible, but only if a significant portion of time is devoted to modifying the package as it stands. Despite this rather disheartening outcome, Sim2Oogl in its present form is a simple, robust programme which quickly and effectively converts data into a form which gives the researcher a "feeling" for the main qualitative features of the system being studied.

6 Conclusions

Barnes referred to the "Antennae" as the "Rosetta Stone" of interacting galaxies. Indeed, this particular system appears to hold a certain fascination for researchers in the field, starting with Toomre and Toomre's simple computer models in the early 1970s; (tenuous) parallels may be drawn between their attempts to decipher the crossed tails of NGC 4038/9 and the early efforts to unravel the secrets of the hieroglyphs. However, as should be clear from this report, a great body of research is concentrated on gaining a comprehensive understanding of the "Antennae". While previous modeled encounters have given promising results, there still exist basic discrepancies between model and observation which must be resolved before this comprehensive understanding can be claimed.

Although my contribution to this field was limited, I feel that my work on the 3D dimensional visualisation of data is of considerable use to researchers. Sim2Oogl is very user friendly and easily modified, a simple but effective tool. The fruits of model matching were less tangible, but I firmly believe that a level of sophistication is possible in automating our matching process which has been absent in other attempts.

7 With thanks to...

I don't think I can thank John Hibbard enough, but I can say that he has played a major part in making my Summer at NRAO one of the most positive experiences I have ever had. He has been a great influence to me over the last few months and has taught me a great deal about the path in life I've decided to take. I want to thank Juan Uson and Jack Gallimore for taking the time to indulge my interests over the course of the Summer; and Tracy Effland and Pat Murphy for making playful computers an altogether less stressful affair.

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8 References

Note: The following references are listed in terms of decreasing usage - some references were purely of historical interest while others played a major role in developing my understanding of the subject. This is particularly true in the case of the first section.

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