orchids that we study), with both biologists and chemists benefitting from joint publications in high profile biological and chemical journals.

***What is the best academic advice you have been given?*** Four pieces of advice stand out for me. Firstly, always negotiate upfront the roles, responsibilities and order of authorship and collaboration. Talking about collaboration, a second piece of good advice has been: by all means test different collaborations, but only stick with the ones that work well. Third, be sure to always do your own field work. On this point, I have been particularly fortunate to work in a department where staff at all levels from the Head of Department down have been encouraged and supported in their pursuit of research topics that require an extensive fieldwork commitment. In my own case, 2 to 3 months of interstate field work per year is the norm. Further, as if by magic, all sorts of issues seem to resolve themselves (or are resolved by others in your absence) while you are largely off grid. Be sure to try it sometime! And finally, never forget that it is a privilege to be an academic.

***What advice would you offer to graduate students and early career researchers aspiring to a career in the biological sciences?*** Never say ‘never’. Across my career, we have made scientific discoveries that were never expected. These discoveries often revealed far more complexity than our initial hypotheses, and sometimes even reversed our prior thinking. Take full advantage of lucky breaks. This could be taking advantage of a rare combination of seasonal conditions to study a new ecological interaction or forging new collaborative partnerships that happen when you accidently cross paths. Be patient! Scientific breakthroughs often take time and can demand patience and persistence over multiple years. Finally, above all, have fun! When the science is no longer fun, it is time to get another job.

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## Quick guide

# Acoustic telemetry

Gustav Hellström[1,*], Robert J. Lennox[2], Michael G. Bertram[1], and Tomas Brodin[1]

***What is acoustic telemetry?*** Acoustic telemetry is an aquatic tracking technology that enables detailed study of the behaviour and physiology of free-roaming animals. The technology consists of two main components: transmitting tags that are attached to animals and emit ID-coded ultrasonic (67–417 kHz) signals, and receivers, which are data-logging hydrophones moored within a waterbody to detect, decode and store the transmitted signals. Modern acoustic telemetry provides researchers with an unprecedented opportunity to remotely collect high-resolution data on free-ranging aquatic animals of (almost) all sizes and over long time periods (up to ~10 years; Figure 1). Further, low-cost, maintenance-free, and autonomous acoustic telemetry receiver networks today constitute the backbone of modern management of fisheries resources. Receivers can now be set out for up to ~5 years and, in some models, data can be extracted remotely by autonomous gliders. In addition, global research collaborations provide common infrastructure that allows researchers to track highly migratory species such as sharks and tunas across oceans.

***What kind of data are collected with acoustic telemetry?*** Acoustic telemetry data consist of timestamped registrations of transmitter IDs that have been detected and stored on an acoustic receiver. Commonly, researchers will acquire the data at the end of a tracking study by retrieving the deployed receivers, although technical solutions now exist where detection data can be relayed to the investigator in real time. The temporal resolution of the data can vary from detections every second (e.g. suitable when tracking fast-migrating fish around hydropower stations) to detections once every few minutes (e.g. suitable when tracking free-roaming fish over long time periods in a lake). When tracking fish over large areas, receivers are deployed in extensive arrays that can cover tens or hundreds of kilometres. The spatial accuracy of detections is dependent on the detection range of the transmitter signal to the receiver (usually a few hundred meters). Given a dense-enough receiver array, a transmitter signal may be detected by three or more receivers simultaneously, which allows for positioning of the transmitter. Such fine-scale positional data can achieve sub-meter accuracy, allowing for the reconstruction of detailed movement paths of the tagged animal. Tags with sensors can also transmit additional information about the animal, such as depth, temperature, activity and even whether the animal has been preyed upon (via a pH sensor detecting the gastric acid of the predator).

***Which research questions can be addressed with acoustic telemetry?*** Reconstruction of the movements of animals tracked with acoustic telemetry using networks or continuous path analysis allows for the calculation of demographic parameters (e.g. survival), spatial ecological metrics (e.g. home range), time-to-events (e.g. dispersal or migration from a site), resource selection (e.g. habitat use) and interactions with conspecifics, competitors, predators and prey. Sensors integrated into telemetry tags can be additionally applied to investigate the thermal biology and bioenergetics of animals in field contexts. Furthermore, acoustic telemetry is an increasingly valuable tool in fisheries management, not least due to the ability to improve estimations of vital rates, such as survival and metapopulation structure. It is also being used to support marine spatial planning and conservation, including identifying critical habitats, evaluating protected areas, estimating dispersal and revealing the impacts of invasive species. Importantly, the unit of replication for most acoustic telemetry studies is the individual animal, generating large volumes of observations per individual that must be accounted for with appropriate consideration of nested effects, as well as spatial and temporal autocorrelation that can confound many traditional analytical designs. Furthermore, the presence of unmarked animals in open natural systems is commonly not accounted for in acoustic telemetry, which may lower the explanatory power of behavioural models.

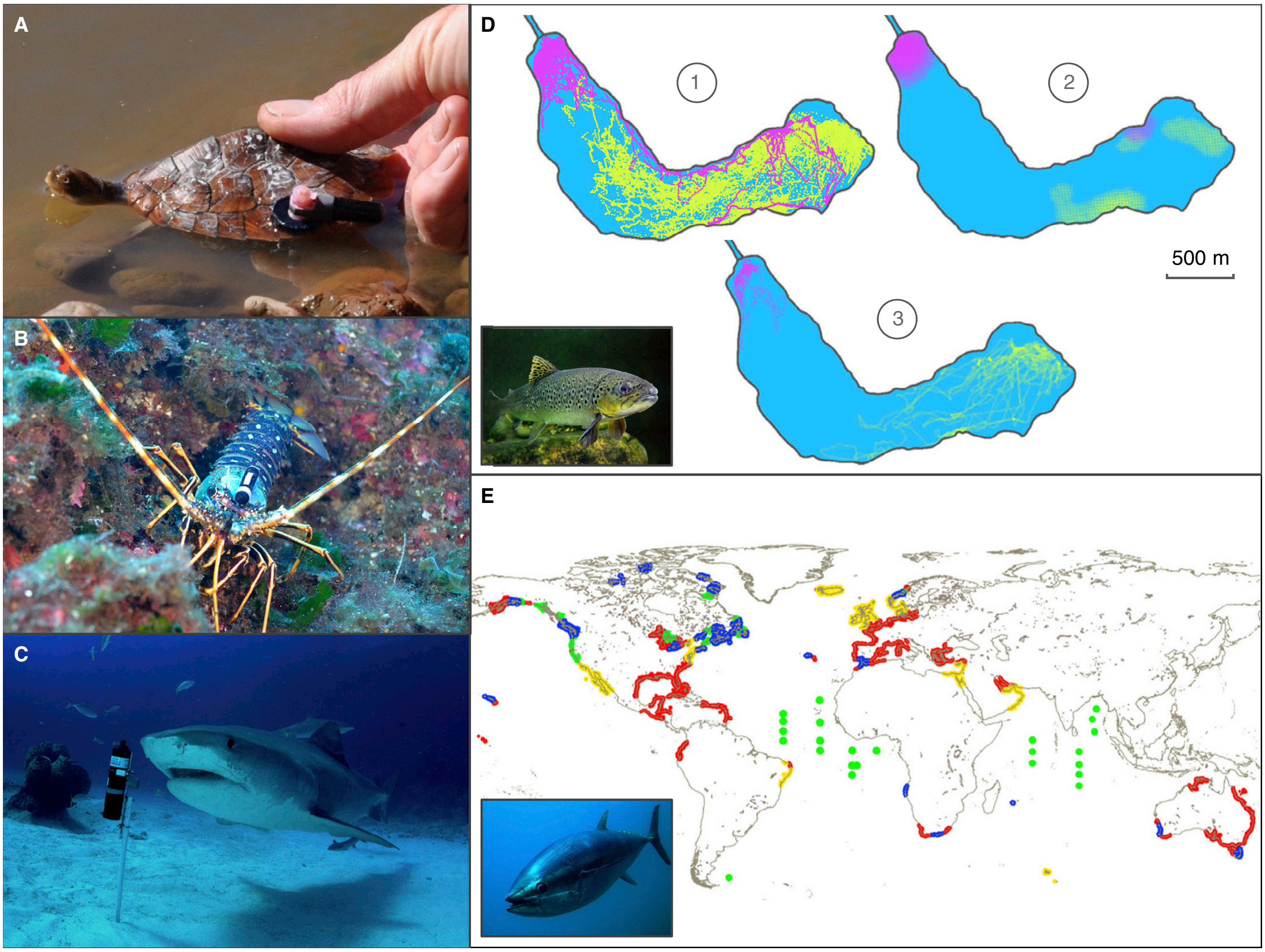

**Figure 1. Acoustic telemetry is a technology used to monitor the behaviour and physiology of free-ranging aquatic animals.**
(A) Acoustic transmitters can be as tiny as a few millimetres in diameter and a fraction of a gram, allowing researchers to track small animals such as this juvenile Mary River turtle (*Elusor macrurus*). (B) Acoustic telemetry is most often used to track animals moving in open water but can also be suitable for benthic species, such as European spiny lobsters (*Palinurus elephas*). (C) A tiger shark (*Galeocerdo cuvier*) swims past an acoustic receiver deployed in the Bahamas. (D) Two brown trout (*Salmo trutta*) are tagged with depth-temperature-acceleration transmitters and released into Vassbygdi Lake, Norway. Known positions of the trout (diagram 1) allow calculation of their home ranges in the lake (2), and acceleration data reveal hotspots and coldspots for activity in the habitat (3). (E) Highly migratory species, such as Atlantic bluefin tuna, are being tracked across oceans using global networks of acoustic telemetry receivers, here depicted as coloured lines and dots representing established receiver networks (blue, green, red), as well as planned networks (yellow). Photo credits: (A) © Hamish Campbell; (B) © V. Maximiliano Giacalone; (C) © Jim Abernethy/Courtesy of the Ocean Tracking Network; (D) © Robert Lennox; (D, insert) iStock.com/abadonian; (E) The Ocean Tracking Network; and (E, insert) iStock.com/Whitepointer.

***What unique insights has acoustic telemetry provided?*** Remarkable insights into the behaviour and physiology of animals have been made with acoustic telemetry, for example regarding the movement ecology of grey reef sharks (*Carcharhinus amblyrhynchos*) in French Polynesia, energy partitioning of sea snakes (*Hydrophis curtus*, *H. elegans*) in Australia and fine-scale details of interactions between climate, behaviour, diet and growth in Canadian lake trout (*Salvelinus namaycush*).

Acoustic telemetry has also been employed to aid species conservation. For example, telemetry was used to identify new spawning grounds of lake trout following a reintroduction program in the Laurentian Great Lakes, enhancing the protection of a fragile population. Long-term tracking of bluefin tuna (*Thunnus thynnus*) with acoustic tags enabled estimating their natural mortality in the Gulf of St Lawrence population at 0.1 per year, providing much sought-after information to improve harvest regimes. Research and management efforts to reduce the impacts of human-induced environmental change has also greatly benefited from acoustic telemetry. For instance, in North America, acoustic telemetry was used to identify aggregations of invasive common carp (*Cyprinus carpio*), facilitating a plan to remove the fish in groups that were located by tracking sentinel individuals. Also, fine-scale positioning of tagged salmon smolts (*Salmo salar*) was used to develop a hydrodynamic model of migration in a river in Norway to understand ways to better attract smolts into a fish passage structure and away from a dam turbine.

***What local and global networks exist for acoustic telemetry data?*** Networks of receivers form the basis of any acoustic telemetry study. These networks may consist of just a few receivers locally deployed in a lake or river. However, given compatibility of the receiver equipment, many independent smaller networks can be scaled up to cover much larger areas. For example, a research group tracking migrating salmon passing a hydropower plant in their local river might become able to acquire information on the whereabouts of their fish far out into the ocean, using receiver arrays deployed by marine biologists. Today, large initiatives coordinating extensive receiver infrastructure exist in North America, Australia, Europe and the global oceans.

***What is the future for acoustic telemetry research?*** Acoustic telemetry technology is evolving at an astonishing pace. Miniaturisation of tags and improved battery technology are continually enabling ever-smaller animals to be tagged and tracked over longer time spans. Underwater acoustic communication protocols and transmission techniques are also being developed to significantly reduce false detections or signal collisions. Moreover, ingenious solutions are facilitating easier deployment and retrieval of receivers, such as automatic downloading of receiver data using autonomous underwater gliders, and robust acoustic release systems integrated into the receivers. The integration of new, advanced sensors into transmitters is continuously progressing, merging the ever-expanding field of biologging with that of telemetric remote sensing. Another particularly promising advance is the continuing emergence of smart transmitters that can sift through large amounts of sensor data (e.g. high-resolution accelerometer data) to detect profiles characteristic of certain behaviours (e.g. spawning, feeding) or physiological states, enabling researchers to remotely acquire information on tagged animals without having to retrieve the tag itself. This approach facilitates the development of real-time detection systems that represent a powerful tool for modern adaptive management, allowing managers to make data-driven critical decisions with minimal lag-time. In parallel, laboratory-based disciplines such as aquatic behavioural ecotoxicology use acoustic telemetry to scale-up their work to the field, to investigate the impacts of chemical pollution on animals in natural settings and at ecologically relevant scales.

***Where can I find out more?***

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## Primer

# Introgression

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Biologists have forever sought to understand how species arise and persist. Historically, species that rarely interbreed, or are reproductively isolated, were considered the norm, while those with incomplete reproductive isolation were considered less common. Over the last few decades, advances in genomics have transformed our understanding of the frequency of gene flow between species and with it our ideas about reproductive isolation in nature. These advances have uncovered a rich and often complicated history of genetic exchange between species — demonstrating that such genetic introgression is an important evolutionary process widespread across the tree of life (Figure 1).

If matings between members of two species produce offspring that are at least partially viable and fertile, such hybrid offspring might reproduce with members of one (or both) of their parental species producing backcrossed offspring. If these backcrossed offspring continue to reproduce with the same parental species, this can result over time in the lasting transfer of DNA from one of the species into the genome of the other (Figure 2A). This process is known as ‘introgression’. Introgression differs from other processes that may produce similar genetic patterns, for example incomplete lineage sorting, because it describes the incorporation of the DNA from one species into another (Figure 2B).

## The extent of introgression

Examples of identified introgression events are distributed widely across the tree of life (Figure 1). From introgression of genes underpinning wing color patterns in *Heliconius* butterflies (Figure 1A) and genes allowing sunflowers to thrive in harsh environments (Figure 1B) to extensive ancient introgression of