Sources and gain in photonic random media

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Context of discovery: a behind-the-scenes story of a thesis

Wat is wetenschap? Wetenschap is de titanische poging van het menselijk intellect zich uit zijn kosmische isolement te verlossen door te begrijpen.

W. F. Hermans, Nooit meer slapen (1966)

Science is much more than the collection of scholarly articles, theses, and books. One might give very different answers to the question what science entails depending on one’s viewpoint. Philosophers of science often make a useful distinction between the “context of justification” and the “context of discovery” when analyzing science. The “context of justification” refers to the rational arguments put forward by scientists that explain why their research belongs to the body of scientific reasoning. The backgrounds of a study, e.g., questions related to why studies are conducted or where a scientist received inspiration for his work, fall within the “context of discovery” [218]. A thesis in physics is mostly written and judged within the “context of justification”. In this section, which does not belong to the academic part of my thesis, I sidetrack a little bit and I describe how scientific research comes into being from the perspective of a graduate student.

The contents of a dissertation in the natural sciences can often only be grasped by a small group of specialized scholars. I am afraid my thesis forms no exception to that rule. For the uninitiated the text of a dissertation is too technical and if it contains a lot of mathematics it might even appear mysterious. A popular saying among physics PhD students goes that the Acknowledgments form by far the most important part of a thesis, simply because it is the only part understandable to everyone. Similarly, the structure and style of scientific articles barely reflect the moments of glory and excitation every scientist feels when making a new discovery. For outsiders, these technical and dry pieces of communication are doomed to remain unattractive prose. For insiders, these texts written in broken English enriched with loads of formulas and graphs possibly reveal beautiful new aspects of nature.

In her 2009 Jan Hanlo-lecture [219] Marita Mathijsen, professor in Dutch literature at the University of Amsterdam, encouraged to introduce all kinds of literary techniques, such as emotion and rhetoric devices, into scientific texts in order to make works of science accessible to a larger audience. This lecture led to vivid discussions in our own laboratory
and culminated in an exchange of ideas between Marita Mathijsen and my promotor Ad
Lagendijk in the Dutch daily *NRC Handelsblad* [220].

To a large extent the difference of opinion originated from alternative interpretations
of what scientific texts are about. Natural scientists are trained to write their reports in a
factual and logical manner. Phrases, graphs, and formulas are constructed with utmost care
to make sure ambiguity is minimized. The reports on their discoveries are primarily aimed at
justifying and placing their newly found knowledge into the existing framework of science.
The bulk of scientific literature deals with this so-called “context of justification”. By
focussing on the context of justification, scientists leave out a lot of interesting information
about the backgrounds of their study that describe how a piece of science comes into
existence. For example, from reading a scientific article in a specialized journal it is very
hard to understand why a particular study was conducted by scientist A or B in the first
place and how and where he conceived the idea for doing so. Analyzing these backgrounds
is done in the “context of discovery” [218]. In contrast to reports dealing with the context
of discovery, the very nature of reports written in the context of justification does not allow
for a lot of flexibility in the way a text is written. Mathijsen’s plea for using literary
techniques boils down to incorporating more context of discovery elements into scientific
correspondence.

The central part of my dissertation, namely the numbered chapters, are written in
the context of justification. In this section however, I want to focus on the context of
discovery of some parts of my thesis. My aim is thus to give the reader some insights in
how experimental science unfolds in practice. More importantly, I hope to show what has
motivated me as a PhD student. As a consequence, this section is free of formulas and
mind boggling graphs, and I have tried to use as little scientific jargon as possible. Every
now and then I allow myself to employ rhetorical techniques to increase readability.

**Conceiving ideas: a bike ride to the rescue**

What to do in four years? Part of the fun of doing a PhD is that you do not have a clear
answer to that question. Most graduate students in physics start off their PhD period with
a project that is thought of by one of their supervisors. Yet a lot of them end up doing
something else in the end. In fact, eventually a PhD student is required to be able to
perform research independently which, in my opinion, includes the generation of new ideas.
Unfortunately, good ideas for new experiments do not pop up out of nothing.

Paradoxically, not understanding something completely might help in getting on the
right track. After all, if you think you understand it all, then there is not much left to
find out. One of the fascinating topics that stayed somewhat of a mystery for me for
a long time, concerned the behavior of a minuscule light source embedded in a strongly
scattering medium. I heard post-docs and professors talking about it, but reading the
original theoretical paper on the subject [51] did not help in gaining a better understanding.
The article was full of mathematical diagrams and terminology I had never heard of during
my studies. I put the subject to rest and focussed on the topic of my Master’s thesis
instead. A talk by my supervisor during one of our meetings with the Complex Photonics
Systems (COPS) group on the third of October 2008 reignited my curiosity on the subject.

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1 Although the distinction between the context of discovery and justification is not always straightforward
to make [221], I do think the distinction describes quite accurately the difference between what we read in
the scientific literature and the day-to-day experience in the lab.
Theoreticians in multiple scattering media completely overlooked the fact that how much comes out of a light source does not only depend on its optical environment, but also on the type of source that is used. His remarks were in complete disagreement with the theoretical paper I had failed to understand initially.

Intrigued by my advisor’s talk I started thinking about an experiment that could reveal the consequences of having different light sources in experiment. I presented an experimental scheme to measure the power balance of sources in random media at one of the brainstorming sessions in our group Photon Scattering in March 2010. The scheme was based on integrating spheres. These hollow spheres typically have a diameter of 10 centimeters and are either coated with white powder or a thin layer of gold. They are often used to measure the total transmitted light through a sample and I thought they would be great instruments for measuring the total emitted power by a light source. One of my senior colleagues Patrick Johnson immediately remarked that this experiment was going to be much harder than I thought. Nevertheless I decided to give it a try. Based on chemical literature I selected some molecular light sources with beautiful names like Rose Bengale and Nile Blue that were suited for the experiment.

After several days of stubbornly trying out the experiment, I concluded however that Patrick’s experience had overruled my naive enthusiasm. There was no way I could make sure that what I measured probed the total emitted intensity. I felt disappointed and was about to return to the subject of random lasers with which I was more acquainted. The cloudbursts that tempered Amsterdam those days did not help in improving my mood either. Naturally, I was already thinking what new random laser experiments to do. During my bike ride home, while getting soaking wet, I suddenly realized that a random laser experiment with different type of sources would be a great way to prove my supervisor’s point. Multiple scattering inside the sample would mimic an integrating sphere. This realization was a thrilling experience. In the next month I conducted random laser experiments, which indeed showed the behavior I expected and eventually led to the work described in chapter 2 of this thesis.

The importance of group discussions and meetings in generating ideas can hardly be overestimated. The third chapter of my thesis followed from a group talk given by fellow PhD student and dear friend Sanli Faez. In his quest for measuring Anderson localization with electromagnetic waves, he had decided to move from light to microwaves. Working with microwaves has two distinct advantages in photonics. First, photonic structures in the microwave regime are on the order of centimeters, which means you can just use a pair of scissors and scotch tape to create your samples. So whereas in optics the radiation is visible, while the sample structure is not, it is precisely the other way around in microwaves: the radiation is invisible, but you do not need a fancy electron microscope to study the spatial structure of the sample. Second, in this wavelength range, materials show a much larger spread in refractive index. I wondered what other types of experiments would be feasible and interesting with this new equipment, so I asked Sanli: why not look at a related phenomenon, namely transverse localization, as well? This topic was very much in fashion at that time due to the fact that some first claims were made regarding its observation. Ad, Sanli, and I were convinced that new physics would arise when studying it in more detail. A new project was born.

Another source of inspiration is of course formed by the scientific literature that is already out there. Unfortunately, staying up to date with the literature has become quite a struggle. The number of interesting articles that appear in scientific journals has grown
tremendously. Moreover, the number of journals that might publish relevant work has also
grown in recent years. For example the Nature Publishing Group has launched at least five
journals that are of interest to my community since 2002. It is therefore nearly impossible
to read and understand every article in your field from top to bottom. Still, reading articles
can be a great way for getting new ideas, because those articles often approach the field
under a slightly different angle. Combined with you own knowledge, this angle might just
be what is needed to create an insight.

Such an insight occurred to me while I was carefully reading a paper in which the output
color of a random laser was manipulated [156]. I liked the paper a lot, because normally
the color that comes out of a random laser is beyond control. To induce a preference for
a certain color, the authors had made multiple scattering media out of spherical particles
with a fixed size. As a consequence some colors remain longer inside the medium than
others, and these are then the colors that are generated inside the laser. The formula on
which their work was based, was very familiar to me, yet I kept staring at it for minutes.
Out of experimental experience and by reading the thesis of Gijs van Soest [89] over and
over again, I knew that the color of a random laser changes due to reabsorption. To my
surprise, there was however no absorption term in the equations of the paper. Clearly, by
engineering the absorption inside the sample, the output color should become tunable as
well. I ordered a suitable absorbing material named Quinaldine Blue and about two weeks
later the first tuning effects became apparent in experiment.

Experiments: when the unexpected becomes the subject

Not every experiment however turns into a success that easily. Unforeseen effects can either
be exciting or a nuisance, but in both cases they require extra work and cause sleepless
nights for the researcher. After all, unwanted “trivial” artifacts such as spurious reflections
or fluorescence from a host medium are not particularly exciting.

While doing the microwave experiment on transverse localization I thought I encoun-
tered precisely such an annoying side effect. The experiment consisted of a lot of nylon
bars placed parallel to each other. These nylon bars were supposed to interact with the
microwaves in such a way that the wave remained confined and would not spread out in
all directions. The experimental results indeed showed this localizing behavior when we
studied an ensemble of samples. So far so good: Ad, Sanli, and I were proud of these first
results.

But when the initial position of the wave changed in one single sample, the confined
output moved in exactly the opposite direction. This observation puzzled us, and for a
long time we thought that the detectors were somehow interfering with the phenomenon
we aimed to observe. In a somewhat naive moment I decided to remove one of the copper
plates covering the sample to see whether we could measure the wave intensity inside the
sample. Nobody of us believed this approach would work, because the job of the copper
plate was to reduce the losses in the system. Removing the plate, we thought, would lead to
a dramatic increase in loss thereby possibly killing the whole effect we were after. Surprise,
surprise, it worked. The losses were lower than anticipated due to waveguiding in the nylon
itself. Not only remained the localizing behavior intact, clear oscillations in wave intensity
were revealed as well.

So the next question cropped up: what on earth were these oscillations? The data
was very convincing, so there was no real need for new experiments. I focussed instead
on modeling the system. At first I solved the relevant equations by a brute force method, which worked but did not give me any real insight. The equations were very similar to Schrödinger’s equation, one of the iconic equations in quantum mechanics. I knew quantum mechanics from my undergraduate courses, but my knowledge had become a little rusty over the years. I redid some exercises that I did in my second year at the University of Twente. The answer was to be found in one of the first chapters, where it was explained in an exercise how adding up several of the system’s characteristic states leads to oscillations. I calculated these characteristic states for my samples and indeed the wave oscillated in exactly the same manner as it did in experiment.

A little understanding

For me, the thrill of seeing one’s own model in agreement with one’s own experimental data, is only rivalled by seeing a sought after experimental effect for the first time. Together they make up for all hours in the lab when things did not work as planned and for all hours spent behind the desk when integrals, impossible equations, and crashing computers test your patience to the maximum. At first glance, it appears that understanding a problem in physics comes down to understanding the maths that describes the phenomenon. The maths can however easily get out of control and although a numerical solution probably yields the correct answer, it does not necessarily lead to understanding. Playing with the input parameters increases the insight obtained with numerics somewhat, but the risk of playing with parameters for weeks without significant progress is a serious danger.

Due to these limitations of numerical calculations, simple, approximate analytical solutions are very much preferred in our group. Sanli referred to this preference explicitly when I showed my first results on light sources and random lasers. He was impressed by the experimental data, but believed an analytical model would be much more powerful than the numerical solution I had presented. He was right. Later on, our analytical expressions showed directly how light sources influence the outcome of the experiments. It still amazes me that our experiments are encapsulated in an expression containing just a handful of characters. All of a sudden, you find yourself with one line that describes the essence of an experiment. To experience such beauty, is the pleasure of doing natural science.